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RATIONALE FOR WINDSHIELD GLASS SYSTEM
SPECIFICATION REQUIREMENTS
FOR SHUTTLE ORBITER

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FOREWORD

This report presents the rationale used in the development of the specification for the windshield system of the Space Shuttle orbiter.

In the appendixes, the specification for the shuttle orbiter glass window panes and examples of proof test calculations are presented. This report is submitted to NASA Langley Research Center by North American Rockwell through its Space Division in fulfillment of requirements of Contract NAS1-10957 as amended.

ABSTRACT

This report contains a preliminary procurement specification for the Space Shuttle Orbiter windshield pane, and some of the design considerations and rationale leading to its development. The windshield designer is given the necessary methods and procedures for assuring glass pane structural integrity by proof test. These methods and procedures are fully developed for annealed and thermally tempered aluminosilicate, borosilicate, and soda lime glass and for annealed fused silica. Application of the methods to chemically tempered glass is considered.

Other considerations are vision requirements, protection against bird impact, hail, frost, rain, and meteoroids. The functional requirements of the windshield system during landing, ferrying, boost, space flight, and entry are included.

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NOMENCLATURE

a	Flaw depth
a_c	Critical flaw depth
a_0	Initial flaw depth
a_s	Screened flaw depth
a_1, a_2	Equation parameters
b	Regression intercept parameter
\mathcal{C}_L	Centerline
F. S.	Factor of safety for the glass windowpane design
K_I	Stress intensity factor
\bar{K}_I	Mean value of K_I
K_{Ic}	Critical stress intensity factor
K_{IcN}	Critical stress intensity factor in liquid nitrogen
K_{IP}	Future value of K_I
m	Regression slope parameter
ML	Mold line
n	Number of data points
N/M	Newton/meter
p	Pressure
$P(Z)$	Probability of event Z
Q	Flaw shape factor

s	Estimate of the standard error about the regression line $y = b + mx$
T	Time of Failure or Time; Value of Students T for $\alpha/2$ and $n-2$ degrees of freedom
t	Thickness
TBD	To be determined
T_M	Operational service life
v	Flaw tip velocity
$V(\hat{b})$	Variance of estimate of b
$V(\hat{m})$	Variance of estimate of m
v_p	Predicted value of V
x	Independent variable
\bar{x}	Estimate of the mean value of x
x_P	Future value of the independent variable x
y_P	$b + m x_p$ (Predicted value of dependent variable)
y	Distance from \mathcal{C} through thickness: estimate of dependent variable
α	Probability that an event will occur.
β_P	One half of prediction interval: $T [s^2 + s^2/n + s^2 (x_s - \bar{x})^2 / \sum (x - \bar{x})^2]^{1/2}$
Δ	Increment
μ	Micron (10^{-6} meters)
σ	Local stress
σ_b	Applied bending stress
σ_c	Critical stress

$\sigma_{C/L}$	Residual stress at the centerline due to temper
σ_{cN}	Critical surface stress in liquid nitrogen
σ_{Cl}	Is $(\sigma_{n1}) (\sigma_{cN} / \sigma_S)$ for thermally tempered glass
σ_{dh}	Surface stress due to thermal temper
σ_{ES}	Maximum applied stress at surface of the glass window panes due to the glass life environmental exposure
$\sigma_{(n)}$	Net surface stress
σ_{n1}	Net surface stress in service glass
σ_{n2}, σ_{n3}	Net surface stress in applied test
σ_{PT}	Applied surface stress in the proof test
σ_r	Net stress combining residual and bending stress
σ_S	Applied surface stress
σ_y	Local stress at y

1. INTRODUCTION

1.1 PROGRAM INTENT

The intent of this program (Contract NAS1-10975) is to define, develop, and test specific structural elements for an advanced window system for the Space Shuttle orbiter. The study baseline was the Phase B orbiter configuration (161C). This report presents the fracture mechanics methods, data, and rationale in developing structural requirements pertinent to design and procurement of the orbiter windshield glass. The windshield designer is given the necessary requirements and procedures for generating acceptance tests and corresponding safe-life spans for the following materials: fused silica (CGW7940), aluminosilicate (CGW1723), borosilicate (CGW7740), and soda-lime glass. Vision requirements, including coatings and optical transmission, are delineated and discussed. Considered and evaluated are temperature limitations and the effects and necessity for protections against bird impact, hail, rain, and meteoroids.

1.2 SCOPE OF REPORT

This report contains in Appendix A a preliminary specification for procurement of a windshield glass system. The main body of the report presents specific design considerations and rationale for those specification requirements developed during this program. Included are criteria used in the design and development of orbiter components.

The rationale contained herein includes the structural requirements of the windshield glass. It encompasses annealed, thermally tempered, and chemically tempered glass. Summarized are the functional requirements of the windshield system during landing and ferry, space flight, and boost and entry. The summaries are based on studies that used the design reference mission (DRM) of the orbiter. References contain details of the analytical effort.

1.3 SCOPE OF SPECIFICATION

Specified are the technical requirements of items to be developed and produced. Also, controls are established to insure acceptability of the equipment. This document contains specific design requirements developed during the program in addition to general design requirements developed for the shuttle configuration. Inclusion of all available requirements in a format

obtained from the shuttle program has resulted in a preliminary specification that can serve as a basis for procurement of flight hardware.

Windshield glass is unique and often novel in its response to environmental factors and applied stresses typical of shuttle design. These responses can result in catastrophe unless window design and procurement are proper. This rational and attached specification are intended to disseminate essential glass information as it applies to the orbiter. This document establishes procedures and instructions for assuring adequate windshield-glass strength; provides workable acceptance test logic, ratios, and procedures; sets up necessary ground rules for procurement; and furnishes a target for design effort. Included are seal and spring configurations that have been tested satisfactorily at the pane-frame interface of the outer and inner panes of the windshield system.

1.4 GENERAL GLASS CHARACTERISTICS

In general glass obeys Hooke's Law up to its point of failure. A failure will initiate only in that part of the glass that is in tension and will initiate only from the surface. A failure due to compression or shear stress is unknown. Failures originate from surface flaws and normally propagate in the direction perpendicular to the applied tensile load. The spread or scatter in bending tests, often used to determine the strength or modulus of rupture of glass, is rather large because the failures in glass originate from surface flaws of randomly varying depth.

Glass material exhibits static fatigue in a humid environment while under tensile load. That is, the strength of the glass decreases significantly with time under static load in a humid atmosphere. The effect is cumulative. To express glass allowables, a complete time-strength curve is required rather than a single constant as is commonly quoted for metals. The strength of a glass structure in a humid environment at a depressed or elevated temperature depends largely on the chemical activity or concentration of the water at that temperature. Typically the strength increases at depressed temperatures. The strength first decreases and then increases as the temperature rises above room temperature. Overall, glass strength is relatively unaffected by temperature when compared to metals.

Glass flaws either do not propagate or do so at a greatly reduced rate when the glass is subjected to stress in a water-free inert environment such as superdry nitrogen, liquid nitrogen, or a vacuum. The strength of glass in a dry environment is dependent upon material composition and flaw size and is essentially independent of the time at load. The strength of glass is considered to have the same value for testing in dry nitrogen, in liquid nitrogen, or in a vacuum.

2. STRUCTURAL REQUIREMENTS

2.1 GLASS FINISHES

The strength of a glass pane is determined by its surface finish. Normal surface flaws in glass generated during the manufacturing process reduce the strength from values well in excess of 100,000 psi to values in the range of 5000 psi (Reference 1). Since this large reduction in strength is a function of initial flaw depth, the strength increase attainable by reduction in flaw size (improved surface finish) is essentially unlimited. The strength will vary inversely as the square root of the flaw depth, and although in practice it is difficult to reduce flaw depths to less than 0.001 inch (corresponding to about 11,000 psi), if such a reduction can be attained, a strength increase will result. Strengths of 500,000 to 2,000,000 psi have been attained by chemical polishing with hydrofluoric acid solutions and by flame polishing small silica rods (Reference 2).

The major source of surface flaws is physical contact with the surface of the specimen. The flaws occur during handling and usage after manufacturing or they may occur during the manufacturing process of grinding and polishing. From the quality standpoint, there is an important difference between these sources of flaws. Those flaws produced by handling or usage may, without significant exception, be detected by visual inspection; those produced as a result of grinding and finishing processes are usually not detectable by visual and microscopic examination, and require an examination through acid etching (Reference 1). This phenomenon is due to the grinding or polishing away of the visible part of the flaw created by the finishing process, leaving only the vertical fracture at the bottom of the flaw, the sides of which are in optical physical contact and not directly detectable by visual means.

The grinding technique used to maximize strength in glass panes is based on work by Jones (Reference 3) and Preston (Reference 4) which shows that the total flaw depth is approximately three times as deep as the depth of the visual pits left during chipping in the original milling operation. Stoll, et al. (Reference 1), formulated and tested a grinding procedure based on the premise that the depth of the visual pit can be considered approximately equal to the diameter of the grinding particle. It follows therefore that the total flaw depth left by each grinding operation is three times the average diameter of the grinding particle, and, if the flaws are to be minimized or eliminated, the depth of material to be removed in each grinding operation should equal or exceed that value. Tables 1 and 2 compare a conventional grinding sequence with a grinding sequence controlled for strength. Figure 1 shows a schematic of the controlled grind.

Table 1. Conventional Grinding Sequence

Operation	Abrasive	Average Particle Size		Material Removal*	
		(mm)	(inches)	(mm)	(inches)
Milling	150 grit diamond	0.1016	0.004	—	—
Fine grind	2F aluminum oxide	0.0304	0.0012	0.0381	0.0015
Fine grind	3F aluminum oxide	0.0203	0.0008	0.0177	0.0007
Fine grind	KH aluminum oxide	0.0139	0.00055	0.0127	0.0005
Fine grind	KO aluminum oxide	0.0119	0.00047	0.0076	0.0003
Polish	Barnsite rouge	—	—	—	—

* Although the amount of material to be removed was not specified, the average material removed is included for purposes of comparison.

Table 2. Controlled Grinding Sequence

Operation	Abrasive	Average Particle Size		Material Removal (Specified)	
		(mm)	(inches)	(mm)	(inches)
Milling	150 grit diamond	0.1016	0.004	—	—
Fine grind	2F aluminum oxide	0.0304	0.0012	0.3048	0.012
Fine grind	3F aluminum oxide	0.0203	0.0008	0.0914	0.0036
Fine grind	KH aluminum oxide	0.0139	0.00055	0.0609	0.0024
Fine grind	KO aluminum oxide	0.0119	0.00047	0.0406	0.0016
Polish	Barnsite rouge	—	—	—	—

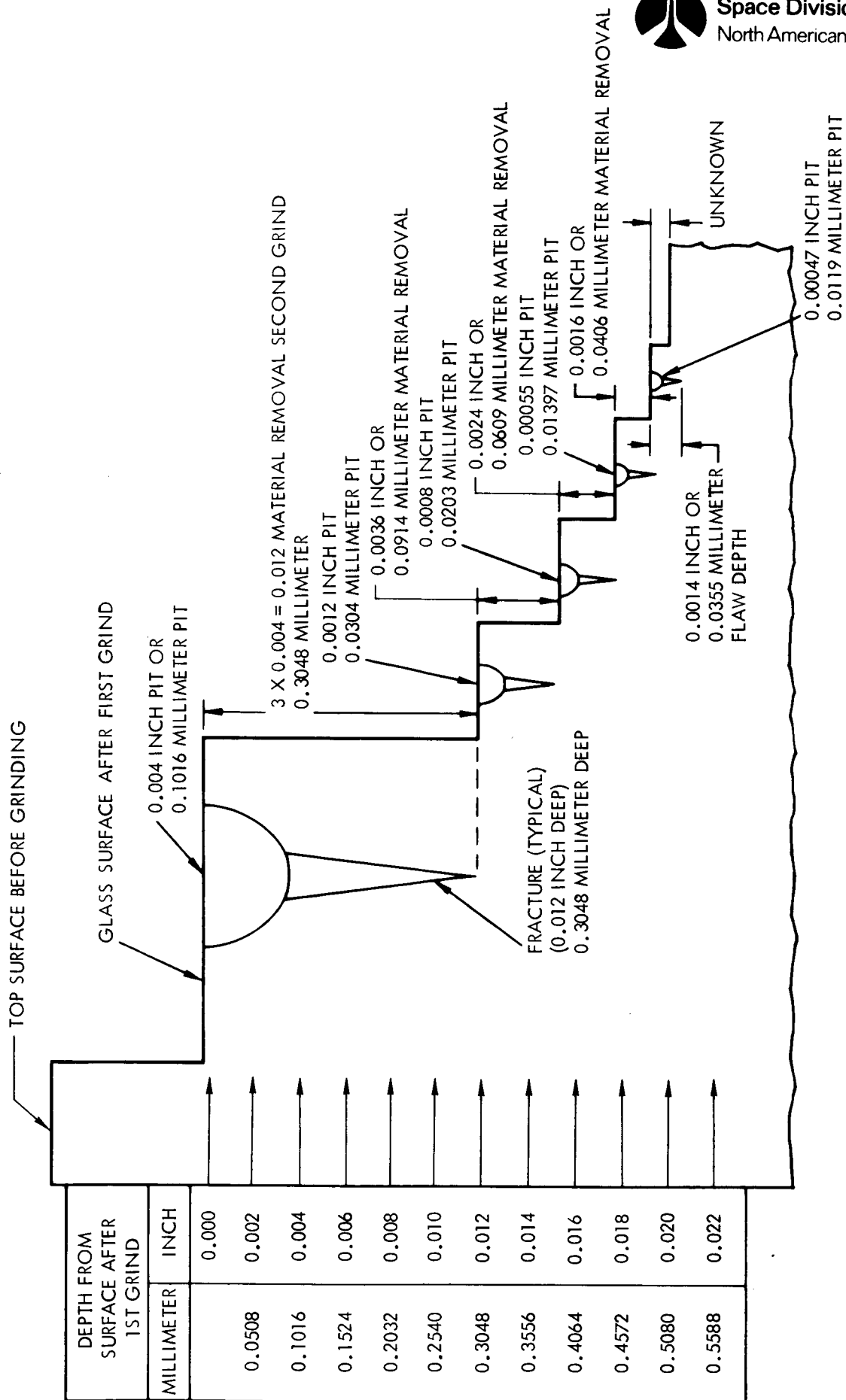


Figure 1. Schematic of Controlled Grinding Process



Controlled grinding is not the only process for improving glass strength, although it may be more predictable in the results produced and more universally applicable than alternate methods. Chemical polishing using hydrofluoric acid solutions is widely used, but is not highly effective on the pure silica glasses. Flame polishing also produces high strengths but both of these methods tend to alter optical qualities and for that reason are normally restricted to edge treatment.

From the procurement standpoint it is important to recognize that there is a difference in the technique of processing glass for good optical and processing it for strength. A company versed in expert optical processing may not be adept at processing for strength, and further, may not recognize that there is a difference. Since normal optical grinding does not control the depth of cut nor often require as many grinding steps as does grinding for strength, such a situation may result in the selection of a subcontractor unversed in interpreting glass strength specifications and least capable of producing the required product.

In the process of establishing design requirements for glass surface finishes it is significant that the grinding process be identified as a critical process and clearly identified for verification during the manufacturing processes. This criterion will provide assurance that the completed glass window will meet the design requirements.

2.2 ANNEALED GLASS

The fracture of shuttle windshield glass would result from glass fatigue under the stresses induced by the mission environments. In particular, the local stresses induced, whether by thermal gradients or pressure differentials across the pane, cause the propagation of surface cracks. The local stress levels are calculated based on engineering analysis. This section of the report derives the proof test requirements used to assure that the glass material meets minimum strength levels to withstand the calculated local stress levels over the service life of the shuttle.

The fracture of glass is due to the propagation of surface flaws under tensile load. These surface flaws appear to be the result of surface damage caused by physical contact with the glass surface during grinding and polishing operations. This surface damage can only be inferred, and is not detectable by visual means. Because of the lack of verification of surface damage and the large scatter in glass strength values, the design approach for spacecraft windows is to subject each glass windshield pane to an acceptance proof test to assure design requirements. In the past, the major problem with acceptance testing of high strength window panes has been the possibility of incurring an indeterminable amount of surface damage as the result of the

propagation of surface flaws during test loading. Quantitative data are now available concerning flaw propagation velocities and critical stresses in humid and super-dry environments (References 2 and 5). The data show that, in a water-free environment, a flaw will not propagate until the critical stress is reached. The flaw then instantly propagates to catastrophic failure. Conversely, in a humid environment at stresses below the critical stress and above a threshold stress, a flaw propagates with predictable velocity. The glass then fractures at the critical flaw depth.

The acceptance proof-pressure test recommended herein takes advantage of the first phenomenon by subjecting each windshield glass pane in a water-free environment to a stress level sufficiently high to show that flaws larger than a designed selected depth do not exist because the glass pane would not have survived the proof test. The second or converse phenomenon is then used to show that the largest flaw which could have survived the test will also survive a desired service life with humid conditions under the reduced space vehicle mission stresses.

The following equation, which relates stress, flaw characteristics, and stress intensity, holds (Reference 17, page 59):

$$K_I = 1.1 \sigma \sqrt{\pi a/Q}$$

where

K_I = stress intensity factor

σ = local stress

a = flaw depth

Q = flaw shape factor

For long shallow cracks, Q may be taken equal to unity (Reference 17). At the critical level when breakage occurs, this becomes

$$K_{Ic} = 1.95 \sigma_c \sqrt{a_c}$$

If the flaw propagation velocity is considered a function of the stress intensity factor, then the time to failure under a uniform stress load may be calculated as follows. By using $K_I = 1.1 \sigma \sqrt{\pi a/Q}$ with an initial flaw depth a_0 , the stress intensity factor may be calculated. The stress intensity factor may be used to determine a crack tip velocity. A new flaw depth can be calculated at some finite time interval $a_1 = a_0 + \Delta a$ and $\Delta a = v \Delta t$. This new flaw depth may be used to determine a new stress intensity factor and hence a new crack tip velocity. By using finite differences and iterating "v" as a function of "a," the integration

$$a = a_0 + \int_0^T v \, dT$$

is carried out. This integration by finite differences is continued until K_I reaches its critical value K_{Ic} at which time the glass fails immediately. This allows the time to failure (T) to be plotted as a function of the stress level for various initial flaw depths (a_0).

For testing in liquid nitrogen or any super-dry environment, the initial flaw does not grow until the stress level approaches the critical stress. The critical stress for breakage in liquid nitrogen then is given by

$$\sigma_{cN} = \frac{1}{1.95} K_{Ic} \frac{1}{\sqrt{a_0}}$$

The necessary proof-test ratio (ratio of the strength of glass in liquid nitrogen to the strength of glass at any given time in a humid environment, (σ_{cN}/σ_c)) can be developed directly by choosing at random a flaw depth (a_0) and by then dividing each value of the static fatigue curve for the chosen flaw depth (Figures 8 through 11) into the liquid nitrogen strength (σ_{cN}) for the same flaw depth (Figures A-10 through A-13 of Appendix A). If this procedure is followed for several flaw depths, it will be found that the resulting curves of σ_{cN}/σ_c are insensitive to, almost independent of, flaw depth. Curves of this type are shown in Figures A-6 through A-9 of Appendix A and are discussed in more detail in following paragraphs.

In the development of data introduced for production use, it is necessary to establish confidence limits in the experimental/analytical data produced. Specifically it is required that intervals be established within which the next data point will fall with some confidence, since the next data point may be vehicle flight. The development of such intervals, called prediction intervals, are generated for the glass crack tip velocities in the following way.

Crack velocity and critical stress intensity factor are material constants for a given composition of glass. Crack velocity data were published by S. M. Wiederhorn (Reference 5). Crack growth was monitored in glass specimens to provide data points of crack velocity as a function of stress intensity factor, K_I (see Figures 2 through 5). Wiederhorn performed regression analyses to obtain least-square fitted lines through the data points. He provides the mean values and standard deviations of slope and intercept for the fitted lines (Reference 5). From these data can be determined confidence limits on the estimate of the regression line. The variance of the mean value of the dependent variable of the experimental data may be calculated following standard statistical practice (Reference 6).

Let $y = b + mx$ be the expression for the regression line, where

y = estimate of dependent variable

x = independent variable

b, m = regression parameters (intercept and slope)

For a future value of x , denoted as x_P , the predicted value of y , y_P , can be estimated by using the regression expression as follows:

$$y_P = b + mx_P \quad (1)$$

Confidence limits can be placed on y_P by considering a confidence prediction interval defined as

$$P \{y_P + \beta_P > y_P > y_P - \beta_P\} = 1 - \alpha \quad (2)$$

This expression states that there is 100 $(1 - \alpha)$ percent confidence that for x_P , the true value of y , y_P , lies within the prediction interval $y_P \pm \beta_P$.

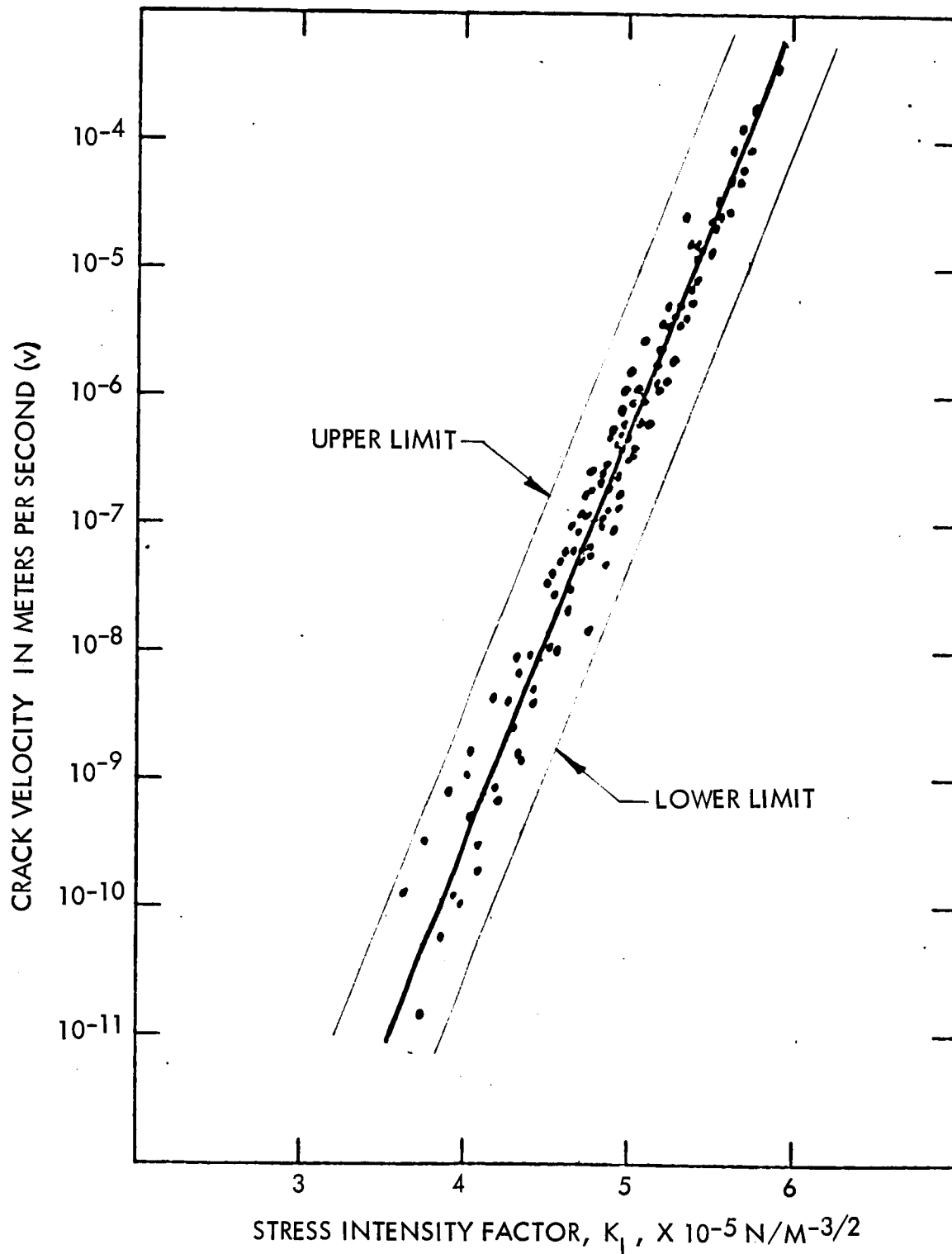


Figure 2. Fused Silica, CGW7940, Air, 100-Percent Relative Humidity

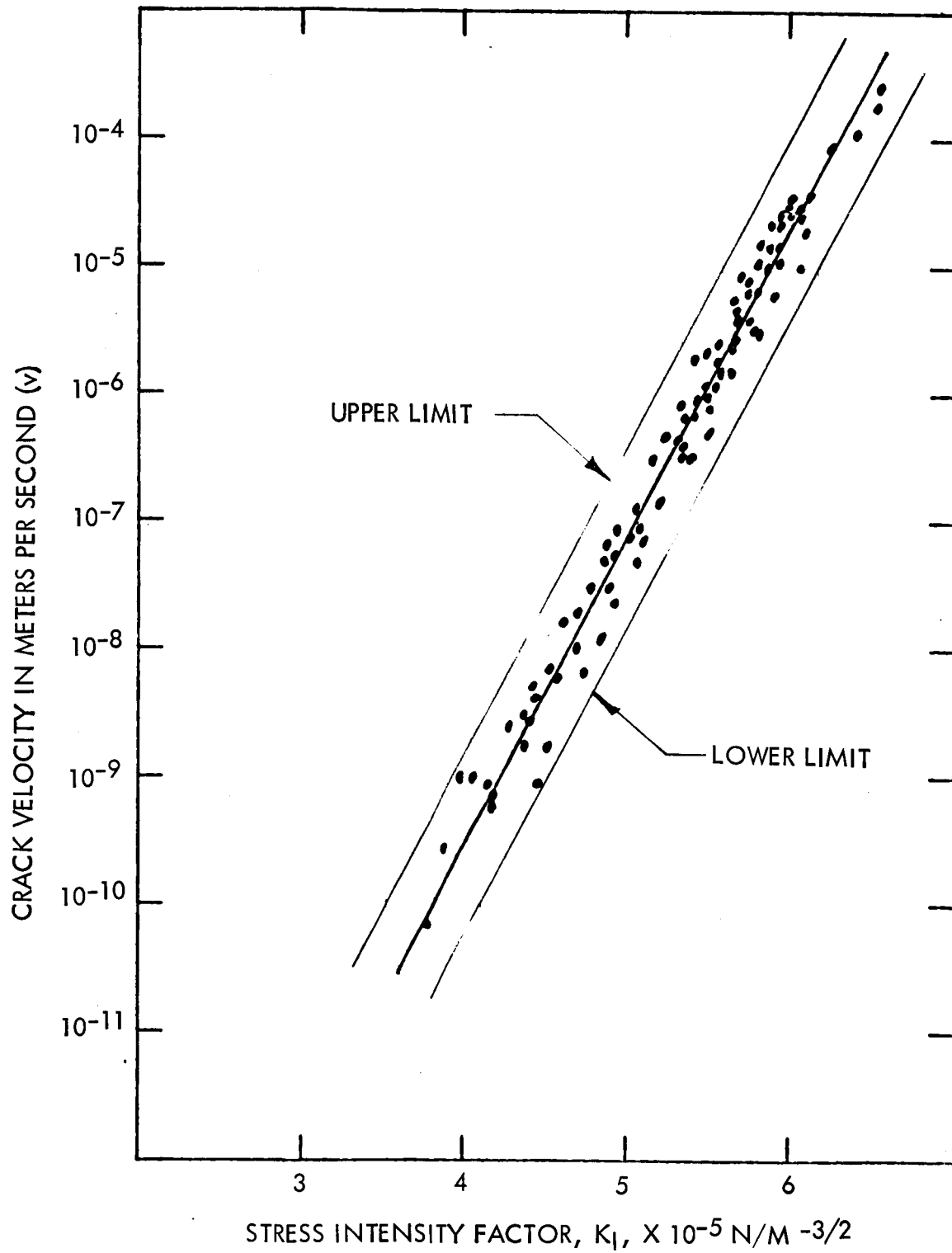


Figure 3. Aluminosilicate, CGW1723, Air, 100-Percent Relative Humidity

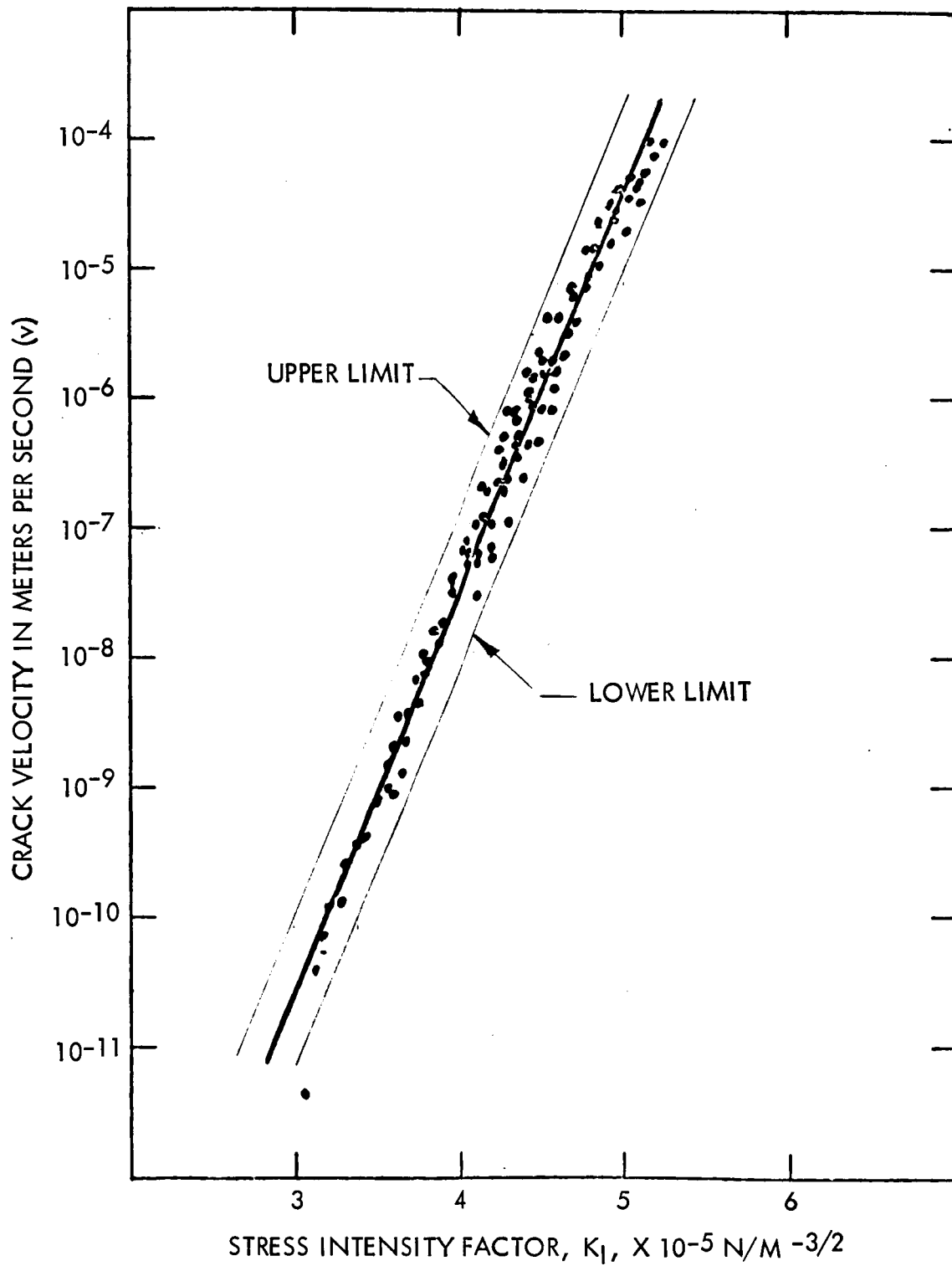


Figure 4. Borosilicate, CGW7740, Air, 100-Percent Relative Humidity

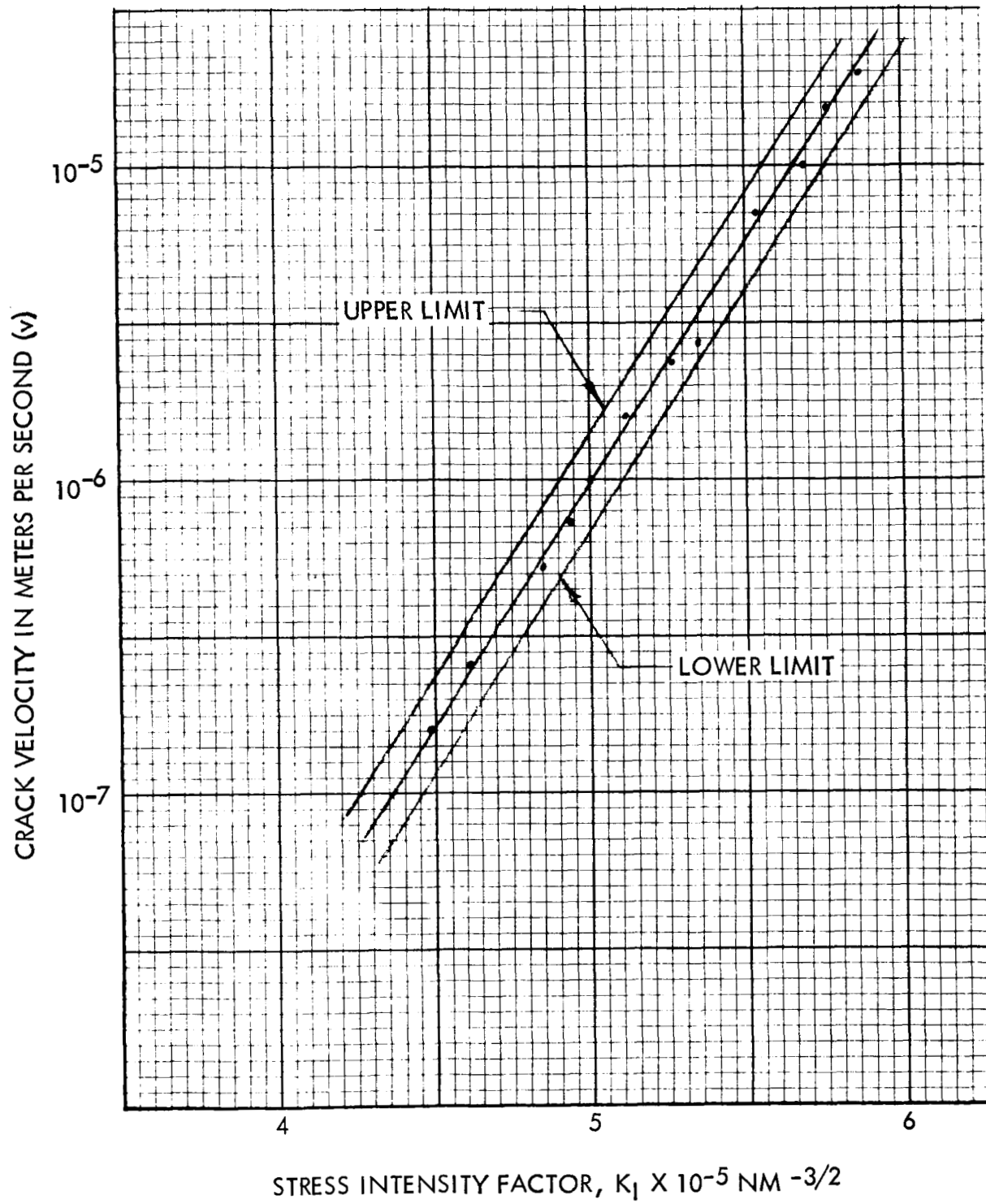


Figure 5. Soda Lime, Air, 100-Percent Relative Humidity

The β_P is determined by considering the variabilities introduced by the data and factors being estimated, so that

$$\beta_P = T \left[s^2 + \frac{s^2}{n} + \frac{s^2 (x_P - \bar{x})^2}{\sum (x - \bar{x})^2} \right]^{1/2} \quad (3)$$

where

T = value of Student's T distribution for $\alpha/2$ and $n - 2$ degrees of freedom

s = estimate of standard error about the regression line

\bar{x} = estimate of mean value of x

n = number of data points

By expanding Equation 3

$$\beta_P = T \left[s^2 + \frac{s^2}{n} + \frac{\bar{x}^2 s^2}{\sum (x - \bar{x})^2} + \frac{(x_P^2 - 2x_P \bar{x}) s^2}{\sum (x - \bar{x})^2} \right]^{1/2} \quad (4)$$

Since the variance of the estimate of b , $V(\hat{b})$, is

$$V(\hat{b}) = \frac{s^2}{n} + \frac{\bar{x}^2 s^2}{\sum (x - \bar{x})^2}$$

and the variance of the estimate of m , $V(\hat{m})$, is

$$V(\hat{m}) = \frac{s^2}{\sum (x - \bar{x})^2}$$

then substitution of these variance relationships in Equation 4 yields

$$\beta_P = T \left[s^2 + V(\hat{b}) + (x_P - 2x_P \bar{x}) V(\hat{m}) \right]^{1/2} \quad (5)$$

Thus, the confidence limits for the prediction interval in terms of the regression parameter variances are

$$y_P \pm \beta_P = y_P \pm T \left[s^2 + V(\hat{b}) + (x_P^2 - 2x_P \bar{x}) V(\hat{m}) \right]^{1/2}$$

The confidence limit prediction interval provides the means of evaluating the expected bounds for a particular observation on a particular specimen by adding the variance of individual observations to the variance of the mean.

If the log of crack velocity, v , is a linear function of the crack intensity factor, K_I , then

$$\log v_P = b + m K_{IP} \quad (6)$$

and

$$\log v_P \pm \beta_P = \log v_P \pm T \left[s^2 + V(\hat{b}) + (K_{IP}^2 - 2K_{IP} \bar{K}_I) V(\hat{m}) \right]^{1/2} \quad (7)$$

Figure 6 depicts these relationships.

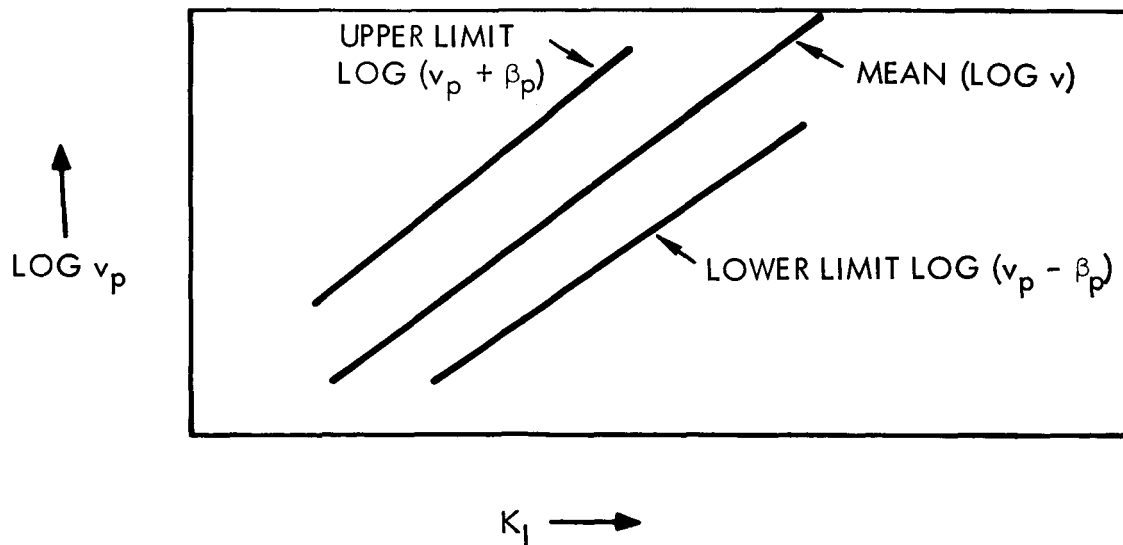


Figure 6. Crack Velocity/Stress Intensity Relationship

Wiederhorn's experimental data have been reproduced in Figures 2 to 4. Data are presented for fused silica, aluminosilicate, and borosilicate, respectively. Figure 5 contains previously unpublished Wiederhorn data on soda lime. Ninety-nine percent confidence limits have been plotted on Figures 2 through 5 according to Equations 6 and 7 and using T-values from Figure 7. Although the prediction interval describes two hyperbolas, symmetric about the mean line, the large number of data points provides a well-defined mean line slope with a negligible curvature of the hyperbolas. Therefore, the bounding lines are assumed to be straight lines. The slopes and intercepts of the mean value and prediction confidence limits are tabulated in Table 3.

The confidence limits so derived were used to generate statistically valid static fatigue curves. A computer program was used to facilitate the calculative procedure outlined in the beginning of this section. This program computes a flaw tip velocity, given the stress intensity and initial flaw depth, and calculates the distance the flaw propagates in a small time increment. This process is iterated until K_I reaches K_{Ic} . The time to failure is then the sum of the time increments for all the iterations.

The results are shown in Figures 8 through 11. The K_{Ic} values were taken from Table 2 of Reference 5. In each case the value used was K_{Ic} minus one standard deviation.

The critical stresses in nitrogen for chosen flaw depths were divided by the static fatigue curves to obtain curves of σ_{cN}/σ_{ES} versus log (mission time).

σ_{cN} was calculated by the equation

$$K_{Ic} = \frac{1.95 \sigma_{cN} \sqrt{a}}{0.00091}$$

where K_{Ic} is the critical stress intensity factor in newtons per meter to the three-halves power, σ_N is the stress intensity in psi, and a is the maximum surface flaw depth in inches. The 0.00091 factor converts from psi $\sqrt{\text{in}}$ to Newtons per meter^{3/2}. K_{Ic} values were taken from Wiederhorn's Table 2 of Reference 5. In this case, K_{Ic} plus one standard deviation was used. This gives a large value of σ_N and thus a conservatively high proof test ratio.

The given curves may be used as follows. If a window must survive a given pressure for a specified time at room temperature, determine first the pressure test ratio σ_N/σ for the specified time from the appropriate

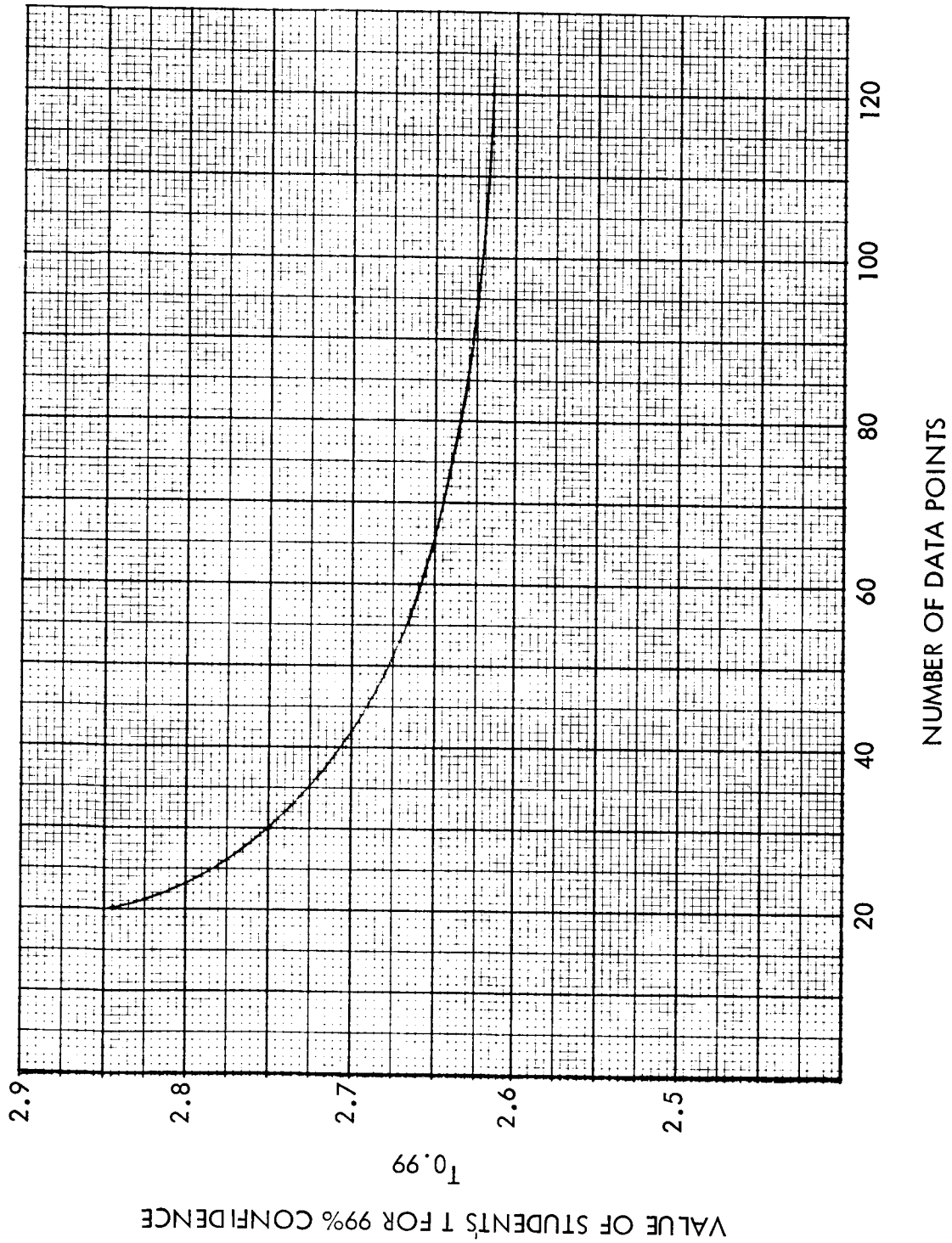


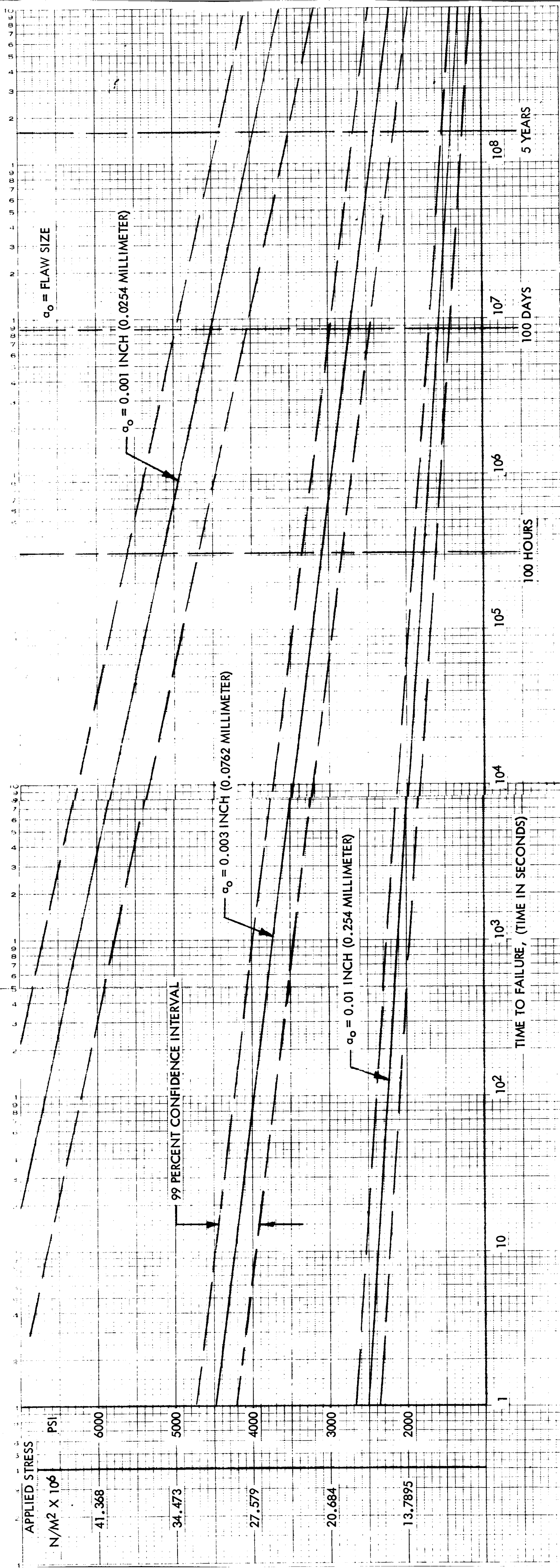
Figure 7. Student's T Curve

Table 3. Mean Values and Confidence Limits for
Crack Growth Formulas

$\log v = b + mK_I$ where $v = \text{crack velocity (meters per second)}$ $K_I = \text{stress intensity factor (Newtons per meters}^{3/2})$			
Glass	Line	Slope $m \times 10^5$	Intercept b
CGW7940 Fused silica	Mean	3.236	-22.43
	Lower limit	3.230	-21.37
	Upper limit	3.242	-23.49
CGW1723 Alumino- silicate	Mean	2.417	-19.21
	Lower limit	2.411	-18.48
	Upper limit	2.422	-19.95
CGW7740 Boro- silicate	Mean	3.071	-19.75
	Lower limit	3.066	-19.14
	Upper limit	3.076	-20.37
Soda lime	Mean	1.540	-13.72
	Lower limit	1.530	-13.52
	Upper limit	1.549	-13.92

curve of Figures A-6 through A-9 of Appendix A. The uppermost value of the curves may be chosen with little penalty in most materials for most times. Next, calculate the maximum stress on the surface of the window due to the given pressure. Then multiply the stress by the pressure test ratio σ_N/σ . This produces the critical stress to be screened. Enter the appropriate curve of Figures A-10 through A-13 of Appendix A with the critical stress and read the flaw size to be screened in the pressure test. If the derived flaw size is greater than 0.003 inch (0.075 mm) deep, then it can be held with normally good grinding and finishing procedures, and the glass may be tested to the indicated pressure test ratio with good chance of success. If the flaw size is required to be smaller than 0.003 inch (0.076 mm), then special grinding and polishing procedures may be necessary to allow the glass to survive the indicated pressure test value.

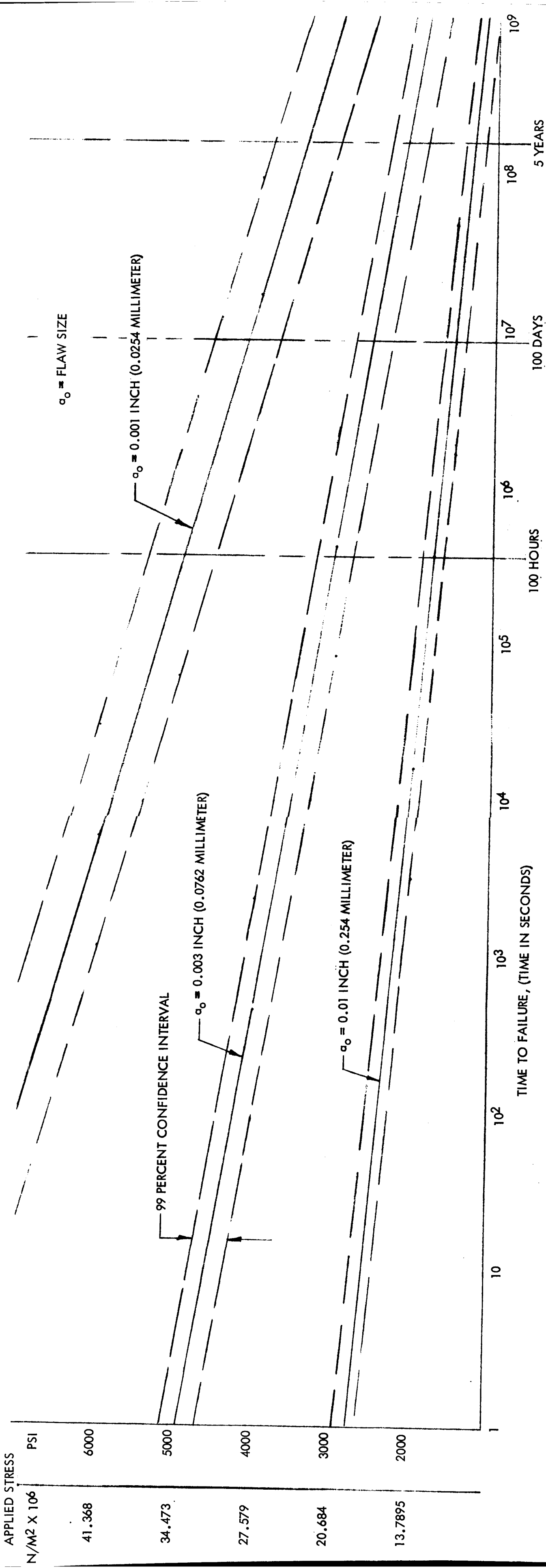
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SEMI-LOGARITHMIC
5 CYCLES PER INCH



FOLD-OUT #1

FOLD-OUT #2

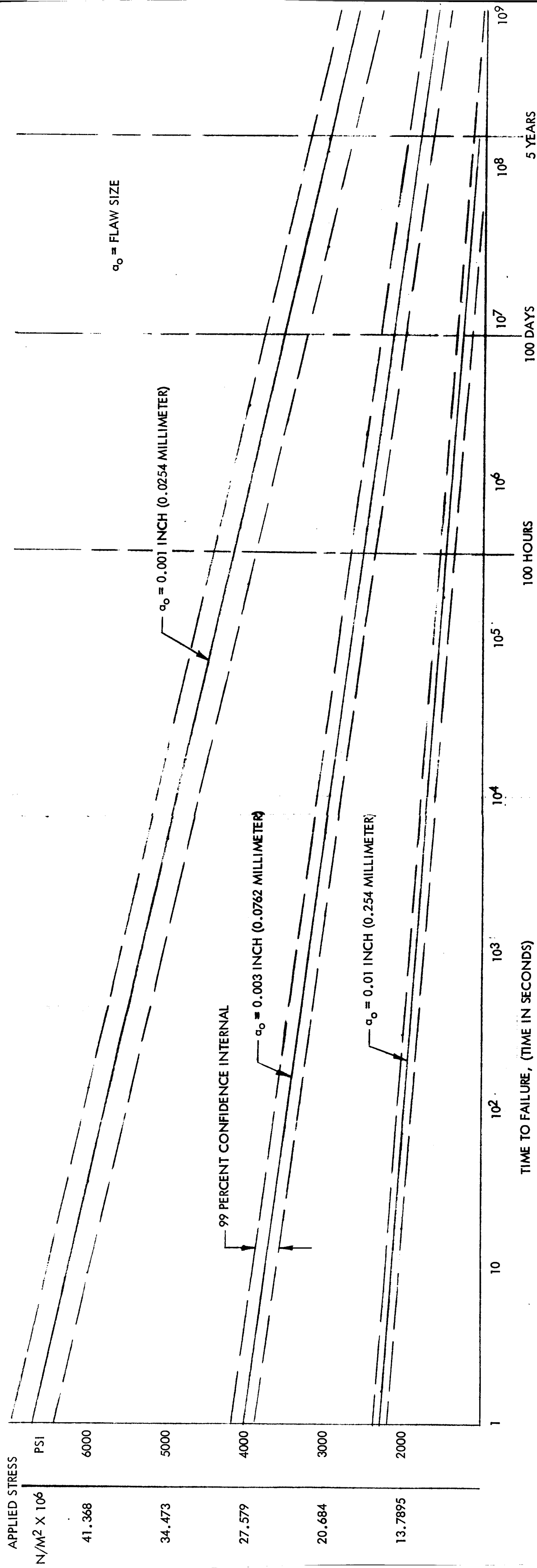
Figure 8. Static Fatigue Curves, CGW7940 Fused Silica



FOLD-OUT #1

FOLD-OUT #2

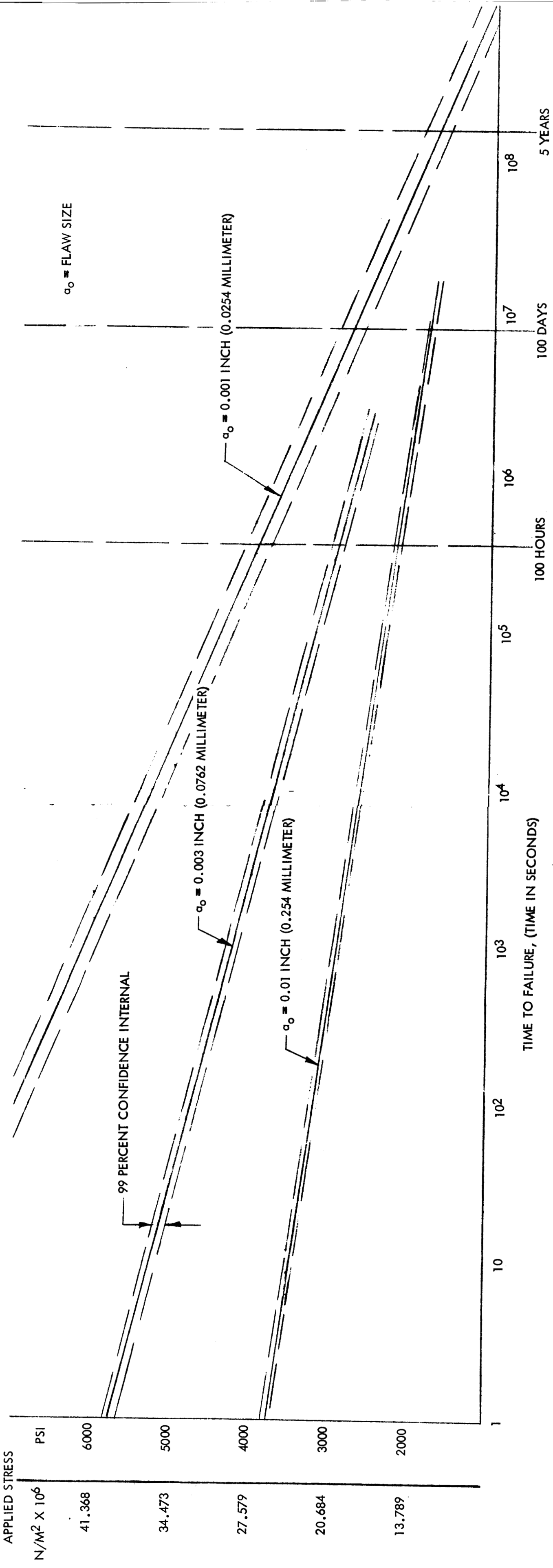
Figure 9. Static Fatigue Curves, CGW1723 Aluminosilicate



FOLD-OUT #2

FOLD-OUT #1

Figure 10. Static Fatigue Curves, CGW7740 Borosilicate



OLD-OUT #1

OLD-OUT #2

Figure 11. Static Fatigue Curves, Soda Lime

2.3 THERMALLY TEMPERED GLASS

The shuttle orbiter windshield glass panes can be designed from annealed or thermally tempered glass. Design considerations for annealed glass have been discussed in Section 2.2 of this report. Thermally tempered glass is analyzed in the same manner with the exception that allowances must be made for the residual stress in the surface of the heat-tempered glass. This section discusses the nature of the residual stresses in heat-tempered glass and indicates the method used to design the proof test for heat-tempered glass window panes.

For thermally tempered glass, it is known that the residual stress is parabolically distributed with respect to thickness. Combining this internal residual stress with the designed surface stress gives the actual surface stress. Once the actual surface stress is determined, the tempered glass is treated like an annealed glass in determining the screened flaw depth.

Derivation of the resultant stress equation when the glass is subjected to uniform bending stress and a parabolic residual stress distribution is given below. Figure 12 as shown is the residual stress distribution of tempered glass and depicts the equation

$$y^2 = -4a_1 (\sigma_y - \sigma_{C/L})$$

which is a parabola with the apex at the $+\sigma_{C/L}$ from origin.

When $\sigma_y = \sigma_{dh} = 2\sigma_{C/L}$, $y = t/2$, and

$$a_1 = \frac{t^2}{48 \sigma_{C/L}}$$

$$y^2 = - \frac{t^2}{12 \sigma_{C/L}} (\sigma_y - \sigma_{C/L})$$

$$\sigma_y = \frac{-12 \sigma_{C/L} y^2}{t^2} + \sigma_{C/L} \quad (8)$$

Figure 13 is a uniform bending stress distribution and depicts the equation $y = a_2 \sigma_b$ which is a straight line distribution with stresses at the two surfaces of $+\sigma_S$ and $-\sigma_S$.

When $\sigma_b = +\sigma_S$, $y = t/2$, and $a_2 = \frac{t}{2\sigma_S}$.

$$\text{Then } \sigma_b = \frac{2\sigma_S y}{t} \quad (8)$$

where

a_1, a_2 = equation parameters

t = total glass thickness

y = distance from C_L through thickness

σ_b = applied bending stress

$\sigma_{C/L}$ = residual stress at the centerline

σ_S = applied surface bending stress

σ_r = net stress combining residual and bending stress

σ_y = stress at y

σ_{dh} = residual surface stress due to tempering

By combining Equations 8 and 9,

$$\sigma_r = \sigma_y + \sigma_b$$

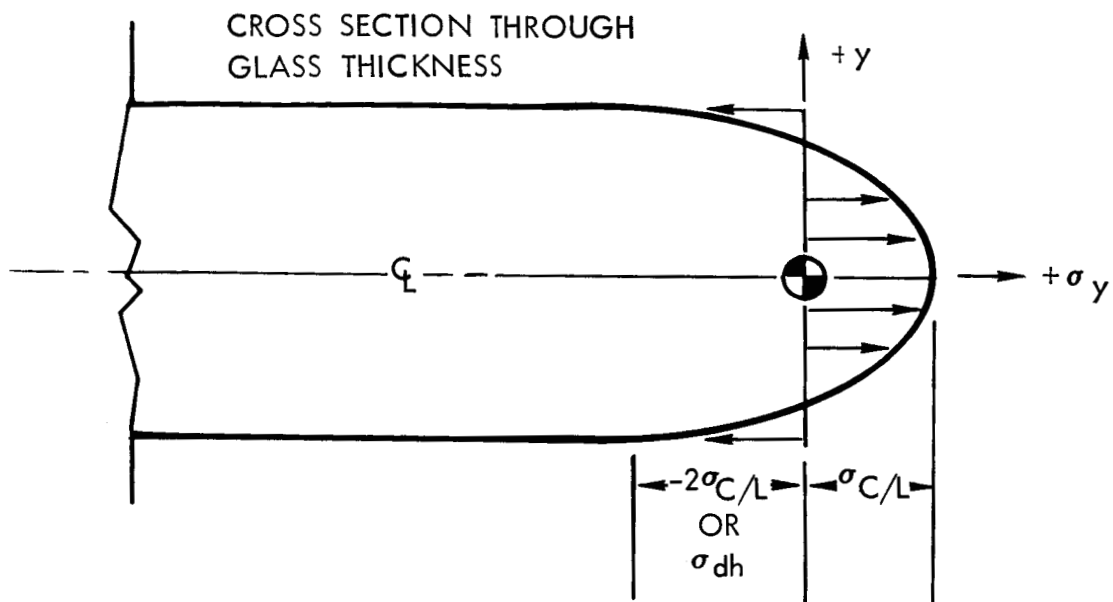


Figure 12. Parabolic Residual Stress Distribution

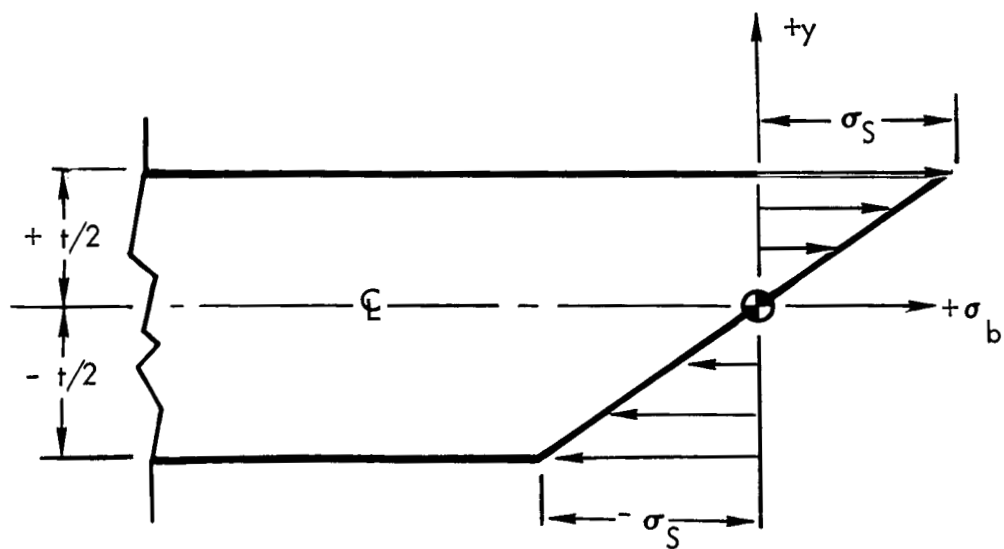


Figure 13. Uniform Bending Stress Distribution

$$\sigma_r = \frac{-12 \sigma_{C/L} y^2}{t^2} + \sigma_{C/L} + \frac{2 \sigma_S y}{t}$$

$$\frac{\sigma_r}{\sigma_{C/L}} = -12 \left(\frac{y}{t}\right)^2 + \frac{2 \sigma_S}{\sigma_{C/L}} \left(\frac{y}{t}\right) + 1 \quad (10)$$

From Equation 10, a family of curves is generated in terms of $\sigma_r/\sigma_{C/L}$, $\sigma_S/\sigma_{C/L}$, and y/t . (See Figure 14.) The residual centerline stress is equal to one-half the surface compression.

The internal stresses at any point can be determined from Figure 14 which is a plot of Equation 10. The surface stress is at $y/t = 0.50$.

Once the net surface stress is determined, the tempered glass is treated like an annealed glass in determining flaw sizes screened. For example, take an aluminosilicate pane 1.0-inch thick with a surface compression of 6,000 psi, and $\sigma_{C/L} = 3000$ psi. Assuming a bending (σ_S) stress of 7000 psi and 100 hours service life, the net surface stress is 1000 psi tension. Then from the aluminosilicate σ_{cN}/σ_S curve (Figure A-7), σ_{cN} equals $2.88\sigma_S$. The net stress to be produced in liquid nitrogen is $(2.88 \times 1000) = 2880$ psi, and the total stress to be applied to produce the net stress and overcome the surface compression is $(6000 + 2880) = 8880$ psi. Flaw size screened is 0.021 inch (Figure A-11). Figure B-1 in Appendix B shows a step diagram for the procedure of analyzing glass. Three different example calculations are also given.

2.4 CHEMICALLY TEMPERED GLASS

Materials used in chemically tempered (chem-tempered) glass are similar to soda-lime but are specially constituted to aid rapid ion exchange. There are three basic methods for chemical tempering. The first consists of heating an alkaline glass in the presence of moist sulfur dioxide or trioxide. The effect is the dealcalization of the surface, leaving a low-expansion surface which goes into compression as the glass is cooled.

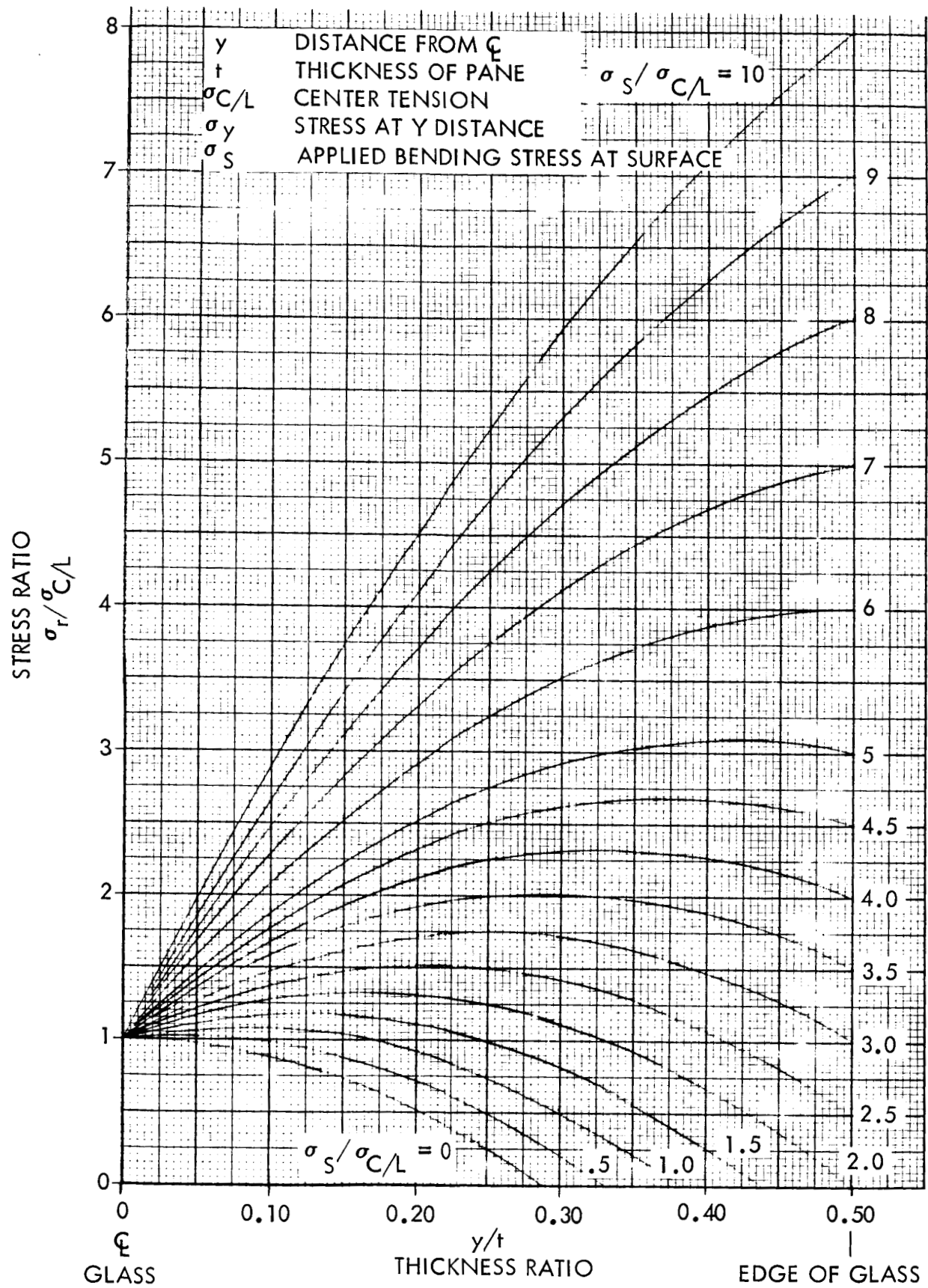


Figure 14. Tempered Glass

The second method consists of replacing the alkaline ion with another ion, giving the glass composition a lower coefficient of expansion on the surface. The alkaline ion is thus replaced rather than removed, but the effect is the same: the surface is compressed as the glass cools.

There are refinements to these two methods, but the basic principle remains the same. The coefficient of expansion of the surface is lowered while the glass is at high temperature; then as the glass cools, the surface goes into compression (Reference 18).

The third method, called ion-stuffing by Ernsberger (Reference 19) consists of "stuffing" large ions into the sites formerly occupied by smaller ones. This is the normal commercial method. Sodium for lithium, potassium for sodium, and potassium for lithium are common. Potassium for sodium produces about 45,000 psi modulus of rupture in abraded glass. Potassium for lithium produces about 70,000 psi modulus of rupture.

Strengthening by ion stuffing can be practiced on ordinary soda-lime glass by using potassium salts; however, the time required for exchange is too long for practical application. Attempts to increase the rate of exchange by increasing temperature reach a quick limit because of the fact that glass will flow at high temperatures, thus relieving the temper. Fortunately, glasses containing high percentages of alumina cut the exchange to approximately one hour and also provide enough thickness to the compressive layer to resist abrasion. Thicknesses of 50 μ to 150 μ are obtainable.

The major emphasis in this design and test program has been directed toward annealed and heat-tempered glass because current anticipations are that annealed fused silica and heat-tempered aluminosilicate glass will be used exclusively in the shuttle orbiter windshield system. Further, there is currently no flaw tip velocity data available for the specially formulated chem-tempering glasses from which to generate stress versus time-to-failure curves. Consequently, no firm conclusions have been reached regarding the applications of fracture mechanics methods (proof testing) to chem-tempered glass. Results of contractual survey of chem-tempered glass characteristics, however, indicate that there are two approaches to proof testing chem-tempered glass that would appear to be consistent with fracture mechanics methods and with results of the annealed and heat-tempered glass studies above.

The first method would amount to treating the chem-tempered glass identically to the heat-tempered glass; that is, in the proof test (conducted in a dry environment or in liquid nitrogen), test the glass in the tempered condition, apply sufficient stress on the surface to overcome the surface compression, and add enough tension to prove the absence of flaws large

enough to propagate to failure in the service life desired. Logic for application of the recommended 1.5 factor would follow the same diagram shown in Figure A-5 for the heat-tempered glass. This method would have the advantage of testing the glass relatively late in the program and would thus minimize the risk of handling damage after test. The disadvantage lies in the large values of compression possible through chemical tempering and the accompanying large absolute value of a small percentage of that compression. That is, if in the proof test one must exceed the high limit of the possible scatter in surface compression due to temper in order to assure conservatively that the correct tension has been applied to the surface for proper flaw screening; and if the actual surface compression in the tested glass is at the low end of the scatter, the tension in the glass may already be at a high percentage of the basic allowable when it is reckoned at zero. For example, in a typical potassium-lithium chem-tempered glass, the compression may reach 60,000 psi, (modulus of rupture 70,000 psi), the basic strength being 10,000 psi. If the compression scatter is reckoned at ± 3 percent, the compression will be calculated to range from 58,200 to 61,800 psi. If the glass is then tested to 61,800 psi plus the tension required by reference to annealed glass proof-test logic, the glass surface is at approximately $3600/10,000 = 36$ percent of its allowable tension at the time surface tension is counted at zero. This disadvantage is not catastrophic, but it will increase the failure rate in proof test, perhaps unnecessarily.

A second and preferred method of proof testing chem-tempered glass to meet fracture mechanics requirements is to test the glass in its annealed state before chem-tempering. Under this method, the disadvantage of the previous paragraph disappears, the worst-case net tension in service can be calculated, and that tension can be applied to the annealed glass to prove the absence of critical flaws exactly as in the foregoing annealed glass logic. This approach is not available in heat-tempered glass because in the heat-tempering process, there are transient differentials which could reasonably be expected to flaw the glass, but there is nothing similar in the chemical tempering process. The disadvantage to this approach is the fact that the proof test would occur earlier in the program than in the first approach, increasing the chance of handling damage after test. The advantages are considered to outweigh the disadvantage, and at this point it would appear that the second approach is more sound.

2.5 TEMPERATURE EFFECTS

2.5.1 Annealed Glass

The effects of temperature on several glass properties were investigated by Kerper and Scuderi for a set of commercially available glasses. The experiments, conducted over a 10-year period for the National Bureau of Standards (Reference 8), were conducted in air with high-humidity content

and were conducted at temperatures ranging from room temperature to the strain point temperature of the glass. The glass materials included most of the materials used in aircraft glazings today: soda lime, two borosilicates, two aluminosilicates, 96-percent silica, and fused silica. The results of the bending modulus of rupture tests are summarized in a 1963 article in the American Ceramic Society Bulletin (Reference 9). For all but the pure silica glasses (96-percent silica and fused silica) and one borosilicate glass, the results indicate a slight drop in strength with increasing temperature to approximately 700 F, followed by an increase in strength back to, or slightly above, the original room temperature strength at just below the strain point temperature of the glass. At the strain point temperature, of course, there is a drop in strength as the glass begins to soften. Fused silica and 96-percent silica show an increase in bending strength from room temperature upward to just below the strain point temperature. Mould (Reference 10) and Wiederhorn (Reference 2) show results for soda-lime similar to those recorded by Kerper and Scuderi — that is, an initial slight drop and then a rise in strength with increasing temperature.

The drop in strength with increasing temperature among the glasses varies with composition, with the severity of the drop being in reverse order to the general temperature tolerance of the glass. Soda lime, a low-temperature glass, appears to take the largest drop, with the aluminosilicate and one borosilicate next in order. The second borosilicate glass, 96-percent silica and fused silica (the highest temperature glasses) took no drop in strength at all for temperatures up to the strain point.

Below room temperature the bending strength of glass rises with decreasing temperature until liquid nitrogen strength is reached. The rise in strength apparently is due to the decreased activity of water. Liquid nitrogen strength is synonymous with vacuum strength, and appears to be related to the basic strength of the glass in the presence of the existing surface flaw pattern.

It is customary to take the lowest strength of glass between liquid nitrogen temperature and the strain point and use that strength throughout the temperature regime as a conservative measure. In view of the rise in strength which occurs both above and below room temperature for the high-temperature glasses, the unlikely possibility that any glass but a high-temperature glass will be used in an annealed state, and the likelihood that increases in strength due to drying of the glass in the vacuum or near vacuum of space will offset the small strength loss which might occur due to increased temperature, it appears reasonable to use the existing room temperature data for design of the shuttle orbiter windshield. Such a generalization should, of course, be assessed for applicability to both the glass material and the design environment prior to its use in detail design.

2.5.2 Tempered Glass

The effects of temperature on tempered glass in general show a reduction of strength above 400 F. Up to 400 F the strength of glass remains constant; then the strength drop varies depending on the temperature and composition of the glass. Stress release occurs at the higher temperature, which tends to reduce the strength. For detail information, see Reference 11.

2.6 THERMAL LIMITATIONS

2.6.1 Outer Pane

The outer shuttle windshield design on the outer surface was tested to a temperature of 1270 F in this contract, NAS1-10957. The stresses produced for this design temperature are limiting for currently known glass materials. (See Reference 7.) Sophisticated and costly active systems would appear to be necessary for temperatures greatly in excess of that value.

2.6.2 Outer Pane Seal

It appears that 1400 F is the upper temperature limit at which significant elastic springback can be achieved using currently known production materials. Elastic springback is necessary for effective sealing. The 1400 F limit is reduced to 1270 F to be consistent with the upper limit demonstrated in the test conducted during this Program which will be reported in SD 72-SH-0123, Space Shuttle Orbiter Window System Final Report.

2.6.3 Middle Pane

The middle window was tested successfully to 570 F during this program. Design action must be taken above this temperature to prevent the hermetic seals from exceeding the 400 F seal limitation.

2.6.4 Inner Pane

The inner surface of the inner pane must not exceed 300 F. This limit is set by proximity of the crew to the radiating surface inside the inner pane. It is judged to be the maximum that can be comfortably tolerated. (See Reference 7.)



2.6.5 Inner and Middle Pane Seal

At temperatures above 400 F, the recovery ratio of the silicon and fluorocarbon candidates for hermetic seal material drop below 80 percent of the compressed deflection and, as a consequence, the seal diameter becomes extremely large. As an example, assuming an O-ring configuration, if the seal temperature rises to 550 F the seal diameter must be about 1.50 inches in diameter. At the recommended 400 F the seal can be designed with a diameter smaller than 0.3 inch (see Reference 14).

3. FUNCTIONAL REQUIREMENTS

3.1 VISION ENVELOPE

The landing mode determines windshield visibility requirements and has been used for the sizing of the vision envelope. Geometry shown in Figure 15 was used in preparing the vision envelope.

MIL-STD-850B establishes requirements for external visibility from the flight crew station of high performance aircraft. The minimum vision envelope established in the specification of Appendix A has been superimposed on the MIL-STD-850B plot for side-by-side pilot aircraft and is shown in Figure 16 for comparison. The vehicle configuration utilized for finite visual definition is the ATP baseline orbiter vehicle. These requirements are yet to be validated by dynamics simulation.

Sufficient vision inboard to see 2 degrees beyond the maximum transient yaw angle is recommended. This is to insure that the pilot never loses sight of the runway centerline during worst-case cross-wind landings. Present conditions down to an altitude of 500 feet indicate a worst transient yaw angle of ± 12 degrees. Therefore, the minimum inboard vision must be 14 degrees.

Rationale for the outboard vision limit is the same as for inboard, plus there must be sufficient vision to see the edge of a runway, on the pilot's side, at the touchdown point 3 seconds prior to touchdown. This is of particular importance during night landings, when runway lights will assist in orientation. This angle has been determined to be a minimum of 20 degrees outboard. Rationale to support this occurs in the case where the orbiter, during an approach at a height of less than 100 feet and a distance of 840 feet from touchdown (840 feet = 3 seconds prior to touchdown traveling at 165 kias or 280 fps), can be subjected to a cross wind of 24 knots. This could cause a transient yaw of up to 8 degrees, 30 minutes. Allowing for the possibility that the orbiter could be as much as 25 feet off the centerline of the runway indicates a minimum angle of 20 degrees outboard (if the transient yaw and the 25-ft misalignment are to the opposite side) is necessary for the pilot to see the edge of the runway at the touchdown point (see Figure 17).

Sufficient vision to see the entire length of a 10,000-foot runway at preflare altitude (1050 feet) with worst-case transients in orbiter pitch attitude is recommended. Pitch transients at this altitude can vary $\pm 1/2$ degree on glide slope and ± 2 degrees on angle of attack. From the

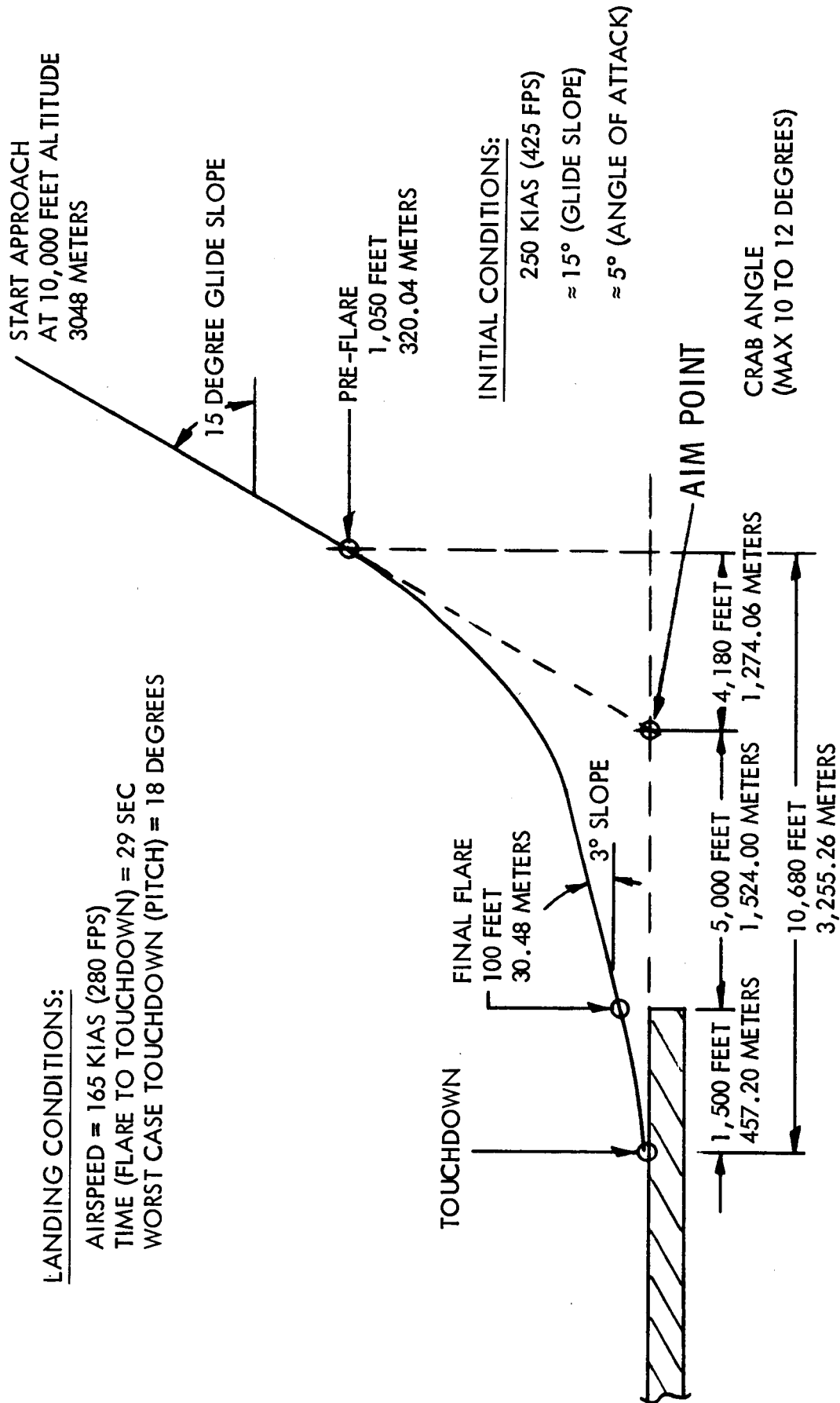


Figure 15. Shuttle Landing Mode Geometry

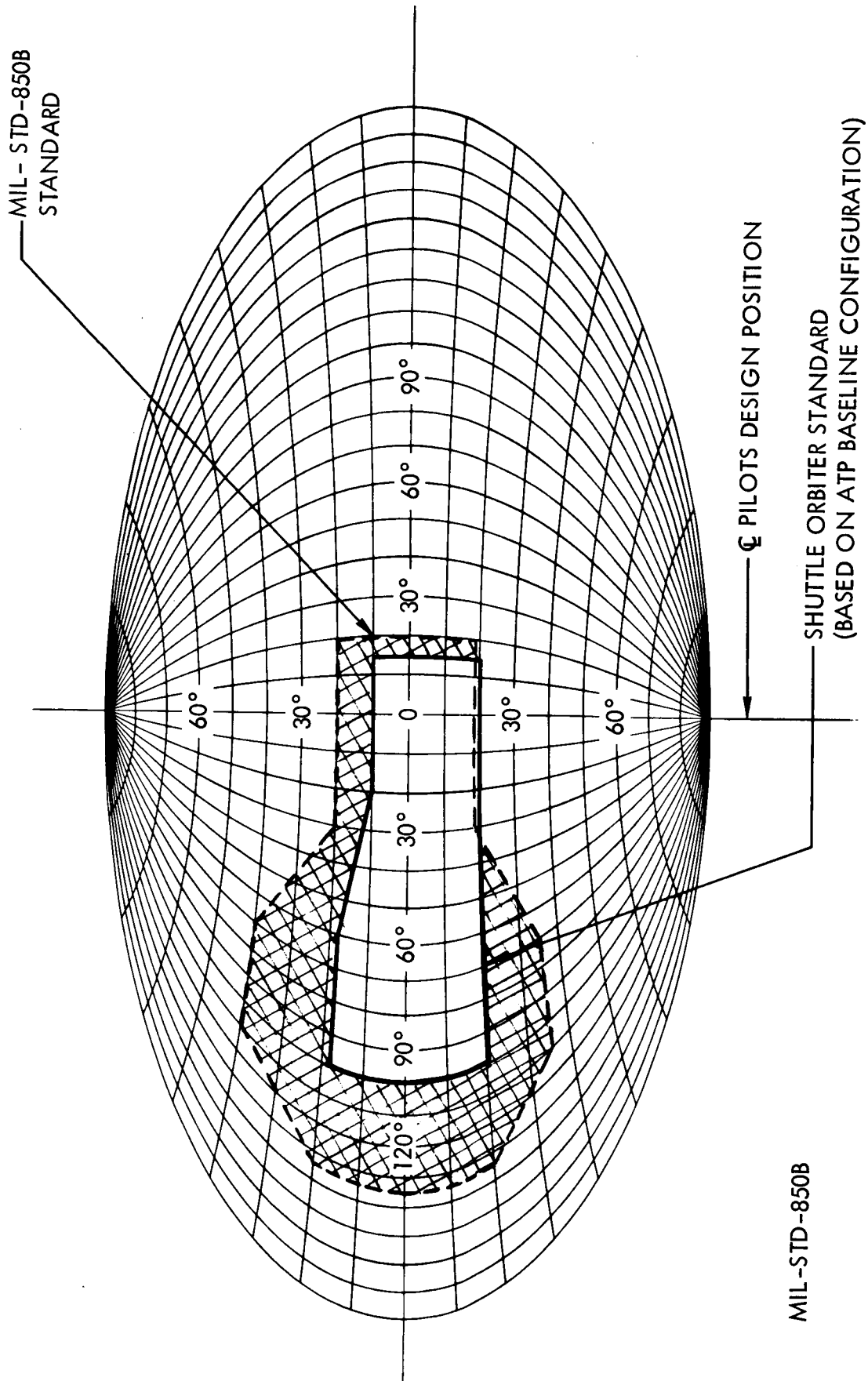


Figure 16. Aitoff's (Hammer's) Equal Area Projection of the Sphere
Orbiter Visibility Standard Comparison With MIL-STD-850B

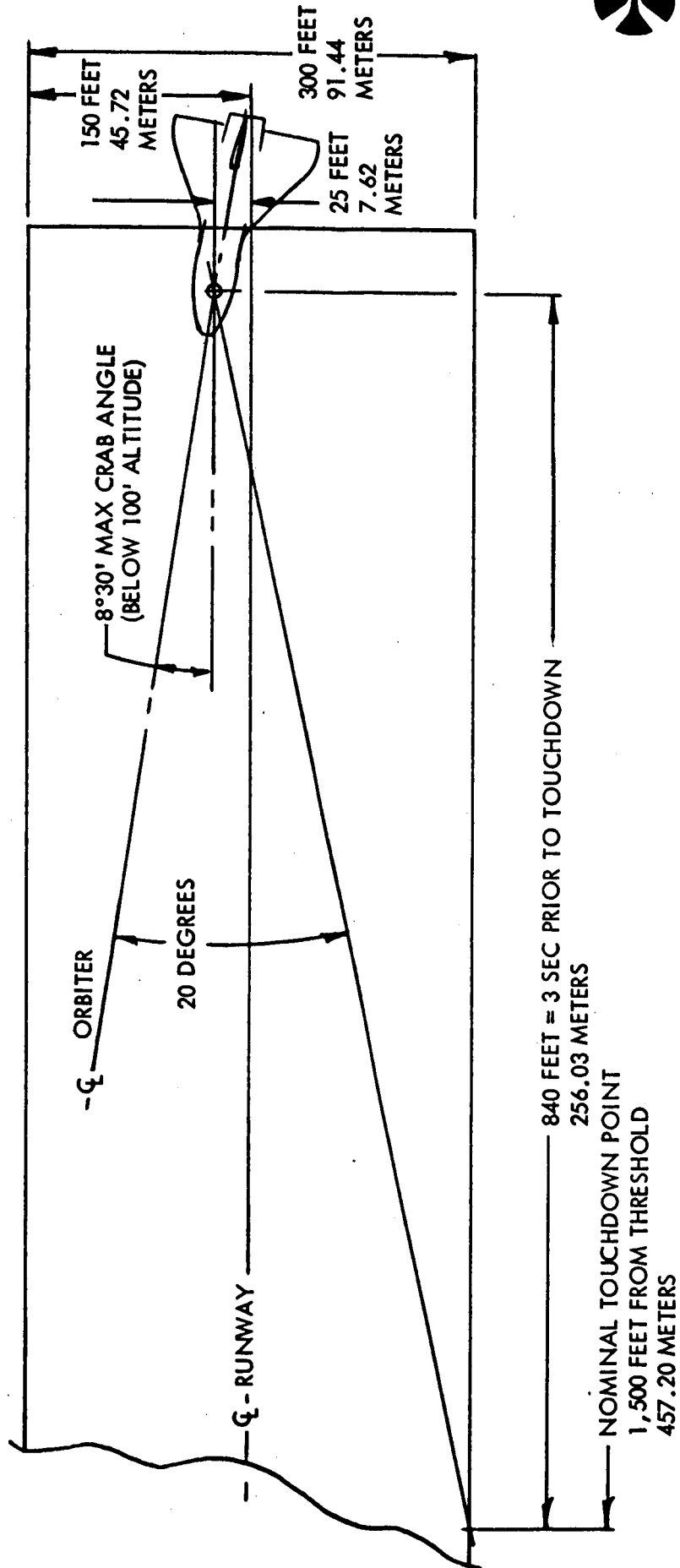


Figure 17. Minimum Forward Window Outboard Vision Requirement Definition

visibility standpoint, worst-case conditions were used: 15-degree, 30-minute glide slope and 3-degree angle of attack.

From these data the minimum up-vision angle of 9 degrees, 22 minutes was established (Figure 18). To insure that the pilot can determine the end of the runway from the surrounding terrain, it is suggested that he be able to see slightly beyond this point. Therefore, a total of 10 degrees up vision is recommended as a minimum.

Vision to see 2 degrees below the horizon at main-gear attitude (tail scrape angle of 18 degrees) is required. This insures that the pilot never loses sight of the runway ahead of him. These requirements dictate a minimum of 20-degree down vision on the pilot's centerline (Figure 19).

Between 20 degrees and 60 degrees left-azimuth vision is recommended to insure an uninterrupted field of view and to help assure that the pilot has sufficient vision for vertical distance judgment during landing. While straight-ahead vision aids in runway alignment, visual cues in the periphery of the visual field help the pilot determine his height and rate of descent. The apparent movement of the ground or landing lights under the aircraft relative to the surrounding land is a function of aircraft height, and the rate of increase in this relative apparent movement is a function of the rate of descent. The smaller the down angle or the further out these cues are picked up, the poorer will be the pilot's judgment of height and rate of descent.

At all points between 60 degrees and 100 degrees left azimuth, the 18 degrees of up vision and 20 degrees of down vision specified are about half those specified in MIL-STD-850B for side-by-side pilots (bomber/transport) (Figure 16). With the present configuration, based on NR crew cabin study No. 12, the outer glass for the side window had to be approximately 60 inches high to provide 40 degrees of up vision and 35 degrees of down vision from the eye position as specified in MIL-STD-850B. This was objectionable structurally and questionable as to necessity. The 40 degrees of up vision and 35 degrees down vision (MIL-STD-850B) were to insure that the pilot could see the horizon out the side without moving his head toward the window during normal bank maneuvers. The 18 degrees of up vision and 20 degrees of down vision still allow the pilot, from the design eye position, to see the horizon during bank of less than 18 degrees. If the bank angle is greater than 18 degrees, he can lean his head outboard to see the horizon through the side window. Movement of the head outboard 14 inches will provide the 40 degrees of up vision and 35 degrees of down vision specified in MIL-STD-850B.

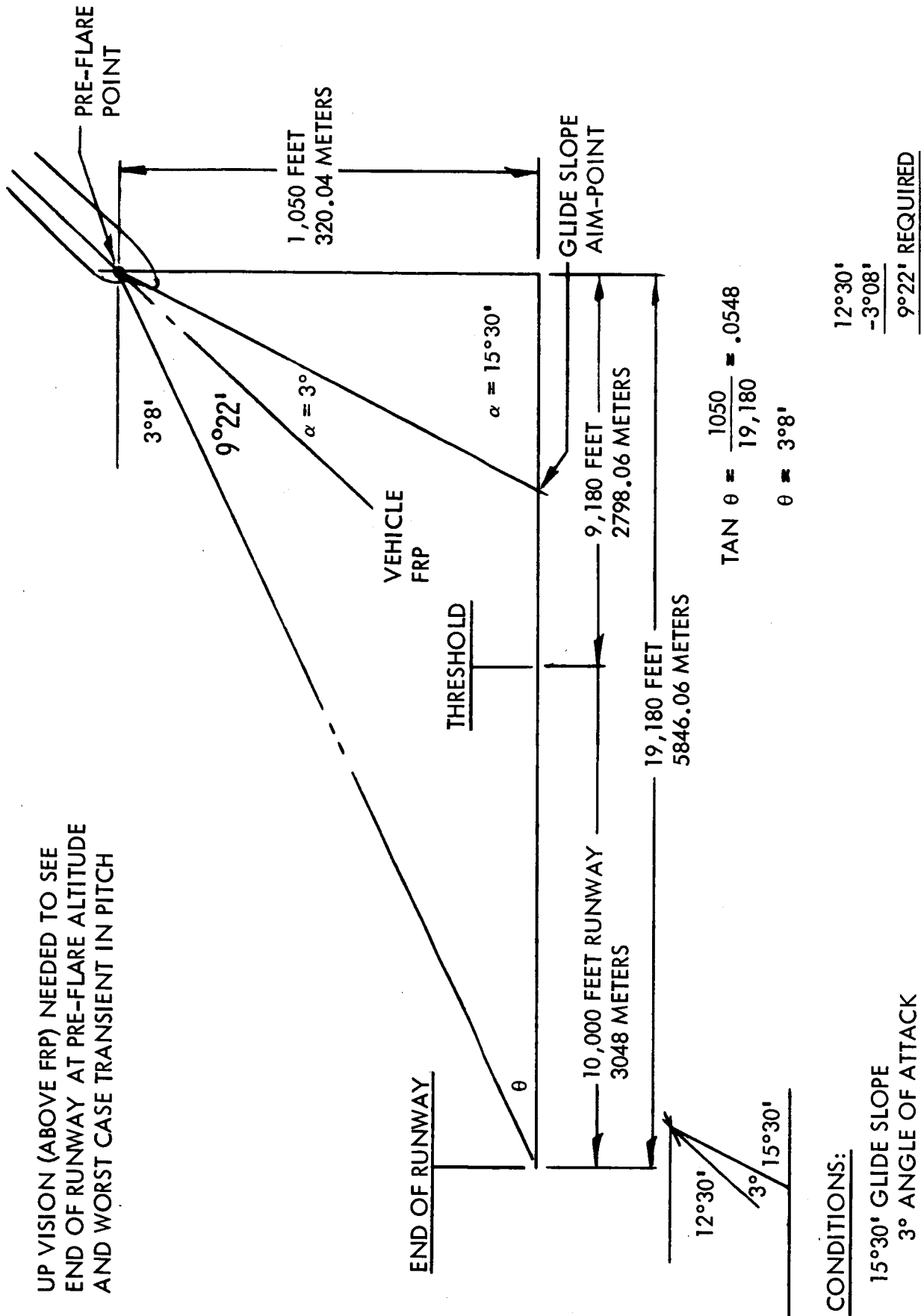
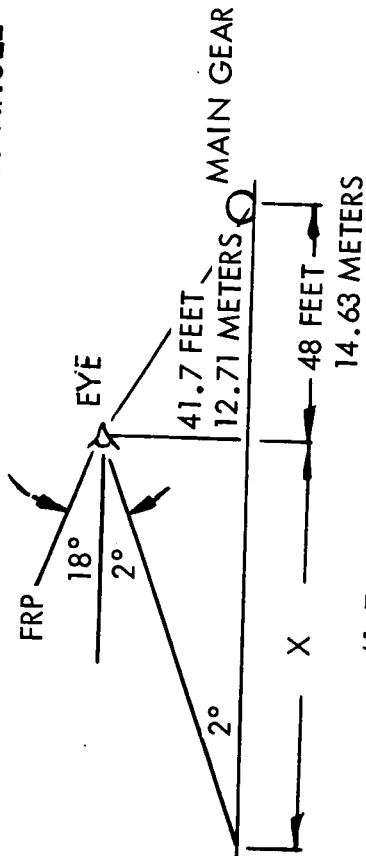


Figure 18. Maximum Forward up Vision Requirement Definition



$$\tan 2^\circ = \frac{41.7}{x}$$

$$X = \frac{41.7}{.035} = 1,190 \text{ FEET}$$

SUFFICIENT DOWN VISION TO SEE 2 DEGREES BELOW HORIZON AT MAIN GEAR TOUCHDOWN AT WORST CASE NOSE UP ATTITUDE (TAIL SCRAPE ANGLE OF 18°). THIS IS TO INSURE THAT THE PILOT NEVER LOSES SIGHT OF THE RUNWAY AHEAD.

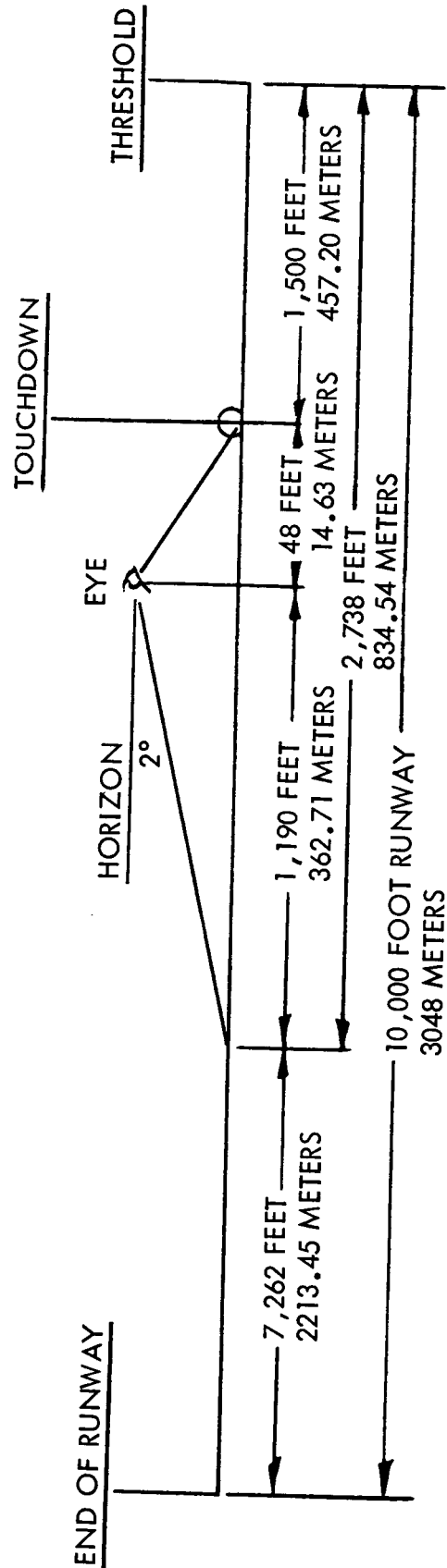


Figure 19. Over the Nose Forward Vision Requirement Definition

The 100 degrees of left azimuth was established to insure that when the pilot looks to the side, he can see straight out without a post (aft edge of window) obscuring his vision. It also allows him to see slightly aft when moving his head outboard without moving it forward. MIL-STD-850B calls for vision to 135 degrees left azimuth primarily to allow the pilot to see the engines, but also to view the wings and landing gear. It is felt this is not necessary for the shuttle orbiter since the crew cannot see the wings, landing gear, or engines on a delta-wing configuration from the flight deck even with mirrors. While it would be desirable to allow the crew maximum side vision, it does not appear to be a requirement for safe and efficient vehicle operation.

Recent simulation orbiter approach studies have been performed at North American Rockwell on orbiter approach and loadings. The studies, utilizing the NR 0007D cockpit configuration, resulted in recommended vision angles for the forward windshield pane slightly less than those derived herein. The simulation studies resulted in a minimum upward vision angle recommendation of 7 degrees instead of 10 degrees. The down-vision angle was reduced from 20 degrees to 18 degrees. The outboard vision was reduced from 20 degrees to 14 degrees. The inboard vision angle of 14 degrees remained unchanged. The simulation studies also evaluated the pilot's visibility in the presence of a straight-ahead windshield post, which blocked the view of the runway, and concluded that such an obstruction was not satisfactory.

It should be noted that the simulation studies have not yet verified the adequacy of the limitations for night operations, nor have they evaluated the effects of variations in approach angle, or of the extent of which "quarter/side" window vision supplements the forward visibility under landing conditions representative of the orbiter. Although the simulation studies reduced slightly the vision limits derived herein, the studies in general tended to validate the analysis presented in this report.

3.2 OPTICAL REQUIREMENTS

The optical properties are a composite from Reference 14 and Reference 15. A specification for minimum optical qualities will be established by the procuring activity.

The requirements for visible light transmittance and ultraviolet (UV) and infrared (IR) transmission are those tentatively agreed upon between representatives of NR and MSC on 2 August 1972. The requirements for a UV optical density of 3 and an IR density of 1 exists on both Apollo and Skylab. An optical density greater than this does not appear to be mandatory at this time for the Shuttle orbiter.

The reflection requirements have been extracted from Reference 16. Reflections from internal sources will be detrimental to safe, efficient operation, especially during dark hours. It is mandatory that light sources be coordinated with respect to the windshield system to minimize reflections. Hence a verification mockup is highly desirable.

Ultraviolet, infrared, and anti-reflection coatings are undesirable due to potential thermal stresses that some of these coatings could impart on the windshield panes and the almost certain damage to any accessible coating during the multiple reuses on Shuttle. Corning Glass Works has suggested that a composition change of the glass could restrict ultraviolet transmission and possibly infrared transmission.

3.3 DAMAGE FROM ENVIRONMENTAL DEBRIS

The possibilities of the orbiter window system sustaining damage from rain, hail, bird impact, and meteoroids have been assessed in References 13 and 7. The conclusions are summarized below.

3.3.1 Rain Erosion

Rain is a concern only below 35,000 feet. A survey of orbiter velocities at 35,000 feet and below shows:

<u>Altitude</u> (ft)	<u>Corresponding Velocity</u> (mph)
35,000	466
30,500	437
20,000	368
10,000	314
1,000	272
Landing	150

It is known that the B-52, 707, 727, 737, DC-8, and DC-9 are flying at 600+ mph with forward-facing, flat glass panes. It was suspected that the onset of rain-erosion damage was at higher velocities than those flown by shuttle orbiter. A check with Wright-Patterson personnel confirmed that rain-erosion problems occur at velocities >500 mph if the glass is abnormally flawed and at greater than Mach 1 if the glass is normally unflawed and canted at an angle of ~15 degrees from normal to the velocity vector. The onset of problems with military aircraft (with windshields canted at a much greater angle) normally begins with Mach 2. Wright-Patterson does not have a recorded instance of an aircraft rain-erosion windshield failure in actual service. It was concluded that the Space Shuttle orbiter was not subject to window damage from rain erosion.

3.3.2 Hail Damage

It is not the current practice to design space vehicles for flight in thunderstorms. Launching during a thunderstorm normally is avoided, as are landings through the area of a thunderhead. Even when flights are made through thunderstorms, hail is rarely present.

For safe operation and landing of the shuttle orbiter after hail impact, the thickness of glass must be such that no through penetration occurs. Below 35,000 feet, stress-raising differential window temperatures and burst pressures are negligible. Crush pressures may be present but generally will cause compression on any hail-damaged outer surface of the windshield. Thus the risk of losing an outer window due to aerodynamic and thermodynamic forces acting on a hail-weakened windshield is small. Damaged windows may be replaced on the ground. The penetration depths have been postulated in Reference 12. The windows will be approximately one-inch (25mm) thick. The penetration is 1/28 of the total thickness which would not be expected to cause direct spalling or failure of the windshield. Thus it is seen that the probability of destruction from hailstones is slight, even if they were encountered.

The probability of encountering hailstones has also been postulated in the reference and shows the probability of the Shuttle orbiter encountering hail in flight is extremely small, on the order of one in 50 million.

These findings indicate no requirement for special precautions regarding shuttle orbiter encounters with hail.

3.3.3 Bird Impact

The Shuttle orbiter vehicle routinely will operate at altitudes from zero to 240 nautical miles (nm) above the earth. During launch, a very minimum of time and a low speed will be associated with operation in the 0 to 1000-foot range. The average bird density in the 0 to 1000-foot-altitude range has been estimated as 0.567 strike birds/nm³. Following aircraft practice, the time period for the Shuttle orbiter landing will be brief with rapid rate of descent. From design data on the shuttle orbiter, the period of time to be spent in the 0 to 1000-foot-altitude range, and the associated shuttle orbiter speed established for each mission phase, the probability factor of no bird impact during the design life has been calculated to be 0.99942 (Reference 12).

The airworthiness standards for transport category aircraft state that if it can be shown by analysis or test that the probability of occurrence of a critical windshield fragmentation condition is of low order, then the aircraft need not incorporate a means to minimize this danger to the pilot from flying

windshield fragments due to bird impact. It is concluded, therefore, that the Shuttle orbiter need not be designed for bird impact.

3.3.4 Meteoroid Hazard

Reference 7 presents two approaches for meteoroid hazard design. The first would be to design the windshield system to provide a high probability of no windshield failure during the vehicle design life. Post-flight windshield inspection (and possible replacement) would be statistically unnecessary from the meteoroid standpoint. The second approach would be to design the windshield system to provide a high probability of no failures during a single design mission and inspect the windows between each flight, replacing them when necessary. An extremely low reliability of the window system associated with the first approach precludes its further consideration (Reference 7). The low reliability is due equally to the extremely long exposure time and to the very small allowable penetrations permitted with the ascent window loadings. The second approach is recommended for the shuttle orbiter. The probability of no failure under this approach is greater than 0.999. For the Apollo command module and service modules, the requirement for meteoroid protection has been that there shall be greater than 0.992 probability of no failure of the spacecraft systems affecting crew safety. Analysis of the Apollo spacecraft has shown a predicted probability of no window failure of approximately 0.998 for the lunar missions. It is suggested that for the orbiter, a reliability for the windshield system of 0.999 should be sufficient, considering the probability of meteoroid-induced failure.

3.4 FLIGHT REQUIREMENTS

Window system design conditions for flight were derived from a design reference mission based on NASA-furnished trajectory data. Total flight functional requirements are considered in three areas: landing and ferrying, space flight, and boost and entry.

3.4.1 Landing and Ferrying

During this phase, environmental hazards such as bird impact, hail, and rain were considered for effects on the window. These effects are discussed in Sections 3.3.1 through 3.3.3.

The probability of the orbiter encountering hail in flight is extremely small, on the order of one in 50 million. It was also considered that if the hail had sufficient hardness and cohesion to penetrate glass, the average penetration would be 0.0229 inches (0.009 centimeters). These findings indicate that no special design precautions are required for protection against hail.

Rain erosion was considered, and it was concluded that the anticipated velocities of the orbiter below 35,000 feet were less than several commercial and military aircraft. From data reviewed it was concluded that rain erosion problems occur only at velocities greater than those currently planned. Therefore, the orbiter will not be subject to window damage from rain.

3.4.2 Space Flight

The probability of windshield failure from meteoroid damage was calculated and the results are presented in Paragraph 3.3.4.

3.4.3 Boost and Entry

The window design environment was developed for the critical entry and boost phases of the design reference mission. Uncovered windows appear to be realizable for the baseline configuration. The thermal exposure encountered upon entry into the earth's atmosphere was analyzed and serves as a baseline for determining allowable exposure temperatures for various window configurations. The analysis was based on the worst case for the forward windshield window. Pressure requirements were obtained from the design reference mission.

3.4.4 Rain, Fog, Mist, and Water Removal

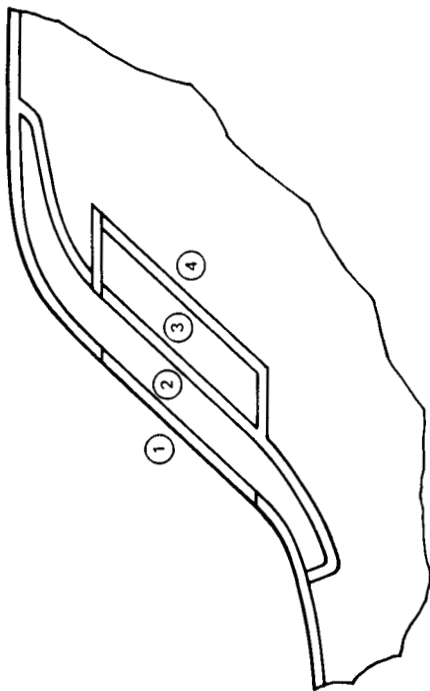
The capability to clear windows of rain, fog, and frost will consider the state of the water condensate, the flight mode, and the design configuration. A sample matrix of flight modes and design considerations is shown in Figure 20. The matrix analysis should consider the following design provisions.

- a. Windshield Wipers: mechanical removal of frost, mist, and water during boost and subsequent flight modes.
- b. Rain Repellant: a pressure fed liquid which when applied to the windshield shall cause impacting water to form in discrete droplets and not form a continuous film.
- c. Windshield Heaters: electrical systems which are attached to the glass and provide a heat source to reduce the formation of frost, fog, and mist at the windshield surface.
- d. Hot Air and Dry Purge: the application of heated and/or dry purges to reduce the formation of fog and mist to remove water vapors from the window cavities.

A back-up system shall be considered for each primary system defined.

MODE	PRIMARY SYSTEM							
	RAIN				FROST			
	①	②	③	④	①	②	③	④
PAD								
PAD ABORT								
BOOST								
BOOST ABORT								
ORBIT								
ENTRY								
PORT ENTRY								
FERRY								

SAMPLE
FORM



NOTE

ABBREVIATIONS TO BE USED
IN FILLING OUT FORM

ABBREVIATIONS	DEFINITION
OK	PHENOMENA IS NOT HARMFUL
NR	NOT REQUIRED - PHENOMENA WILL NOT OCCUR
RR	RAIN REPELLANT-APPLICATION REQUIRED
EC	ENVIRONMENTAL CONTROL
DP	DRY PURGE - GAS
WH	WINDSHIELD HEATER
MW	MECHANICAL WIPER

Figure 20. Matrix of Flight Modes and Design Considerations

4. OTHER SPECIFICATION REQUIREMENTS

The procurement specification contains several technical requirements applicable to all orbiter equipment. The rationale, including those requirements in the specification, reflects the identification of all design requirements that have any impact on the windshield glass specification.

The applicable documents reflect those specifications and documents considered and employed in the detail design, fabrication, and test. A separate paragraph on seals has been included because a major effort was expended on the search for an outer-window seal capable of satisfying the requirements of high-temperature material compatibility and multiple spring load cycles. The design of seals affects the design of window and must be established to limit perturbations on design of the window glass or surrounding structure.

5. ADDITIONAL DEVELOPMENT REQUIREMENTS

The behavior of tempered glass is not well defined. Additional data are necessary with respect to the behavior of thermally and chemically tempered glass. The absence or presence of surface flaws which might extend through the compression layer into the tension layer should be investigated. Current recommendations assume the presence of such flaws and the rather severe penalty exacted by this assumption may be unnecessary. The behavior of flaws in the presence of the compressive layer produced by tempering has not been investigated. In general, a program to research methods and procedures for strength analysis and testing of tempered glass is needed.

A limited amount of data is available on the effect of the various processing variables on the surface flaws of glass. Additional data on the effect of various manufacturing processes would be beneficial. The program should include the effects of downfeed rate, run-out, cooling, and grit size on the various commonly used spacecraft glass glazings. The effect of temperature on glass strength is known but not understood. More data on temperature effects for crack velocity and stress intensity factors are required. Temperature regions beyond the limits of liquid water should be considered. Data should be taken in various mediums, including air, gaseous nitrogen, and vacuum, to verify the independence of strength and fatigue life on environmental parameter other than water activity. Also, the time-dependent effects of transition from the humid environment to hot, dry, and vacuum environments should be considered. There are several promising new materials, such as Corning's ULE-fused silica laminate, which are just out of the laboratory phase and should be examined and tested relative to production usage. These materials may solve many current problems but additional data must be developed on design and production feasibility prior to their use. Even for annealed glass confirmation of time versus strength of glass panes needs to be verified through additional experimentation. Time versus strength curves for annealed glass were developed, using uniform stress fields from Wiederhorn's data on crack velocity versus stress intensity factor. The assumption of uniform stress fields appears to be valid based on the small size of the flaws which exist when flaw propagation rates reach critical velocities; however, the theoretical results should be verified by experimentation. Additional data would be useful regarding the internal stress distribution in chemically tempered glass.

Research on sealing materials and methods for seal to operate at temperatures in excess of 1400 F is needed. The data are needed because the possibility exists that operating temperatures may exceed 1400 F for

the window system. Both plasma-type (outer) seals and hermetic (inner) type seals should be included in the research.

Further studies are required to establish minimum visibility requirements for the orbiter operations. The requirements should be defined relative to the various operational phases of air vehicle usage. Despite years of experience at landing aircraft, there are no definitive minimum visibility requirements for an aircraft windshield system. Present requirements represent optimum reasonable visibility requirements.

The above research represent state-of-the-art development and should significantly contribute to a more cost effective and sounder windshield system design.

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RELATED DOCUMENTS

SD 71-134-1, Technical Proposal for a Window System Design and Test Program for Space Shuttle Orbiter (16 April 1971).

SD 71-172, Space Shuttle Orbiter Window System Design and Test Program Design Conditions and Candidate Window Concepts Report (August 1971).

SD 71-358, Space Shuttle Orbiter Window System Design and Test Program Phase I Study Report (December 1971).

SD 72-SH-0040, Space Shuttle Orbiter Window System Design and Test Program Test Article Final Design Report.

SD 72-SH-0123, Space Shuttle Orbiter Window System Final Report.

APPENDIX A
WINDSHIELD GLASS SPECIFICATION



PREPARED BY	CODE IDENT. NO.: 03953	NUMBER MC332-0006
	SPACE DIVISION	TYPE
APPROVALS	NORTH AMERICAN ROCKWELL CORPORATION 10714 LAKEWOOD BOULEVARD • DOWNEY, CALIFORNIA 90241	DATE
	SPECIFICATION	SUPERSEDES SPEC. DATED:
		REV. LTR.
		PAGE 1 of
TITLE WINDSHIELD-GLASS PANES, SPACE SHUTTLE ORBITER		
<p style="text-align: center;">PRELIMINARY</p>		

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6.	DEFINITIONS

1. SCOPE

1.1 Scope. This specification defines the structural and functional requirements for the Space Shuttle Orbiter windshield glass panes.

1.2 Intent. It is intended that this specification be used as a guide in the design and procurement of a windshield glass system that will provide safe, efficient landings, cruise, orbital operations, payload handling, and takeoffs at any Orbiter compatible airfield in daylight or darkness.

2. APPLICABLE DOCUMENTS

2.1 Applicability. The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of a conflict between the documents referenced herein and the contents of this specification, this specification shall take precedence.

SPECIFICATIONS

Military

MIL-I-26860A 24 July 1958	Indicator, Humidity Plug, Color Change
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MIL-H-46855	Human Engineering Requirements
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STANDARDS

MIL-STD-810 29 September 1969	Environmental Test Methods
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MIL-STD-794 27 May 1970	Parts and Equipment, Procedure for Packaging and Packing of
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MIL-STD-129 28 December 1964	Marking for Shipment and Storage
---------------------------------	----------------------------------

MIL-STD-1472A	Human Engineering Design Criteria
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HANDBOOKS

NASA

NHB6000.1(1A) December 1969	Requirements for Packaging, Handling & Transportation for Aeronautical & Space Systems, Equipment & Associated Components
TMX64589 10 May 1971	Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1971 Revision
TMX64627 15 November 1971	Space Environment Criteria Guidelines for Use in Space Vehicle Development, 1971 Revision
SP8013 March 1969	Meteoroid Environment Model - 1969 (Near Earth to Lunar Surface)

3. REQUIREMENTS

3.1 Item Definition. The Space Shuttle Orbiter windshield glass system consists of those elements of the Orbiter vehicle which are installed into configuration to allow external visibility. The Space Shuttle Orbiter windshield system includes panes, seals, and frames for the forward six windows. An individual window consists of a single series of individual inboard to outboard panes, the seals and/or seats supporting the panes, and the surrounding framework. The windshield glass panes are those single elements of the windshield system which are of glass material and are transparent.

3.1.1 Item Diagram. The location and approximate configuration for the Space Shuttle Orbiter windshield windows are shown in Figure A-1.

3.1.2 Interface. The structures of the windshield system interfacing with the windshield glass pane are as follows.

3.1.2.1 The seal configuration for the window panes is shown in Figure A-2.

3.1.2.2 The outer window seal is of the tadpole type design as shown in Figure A-3 to provide plasma sealing.

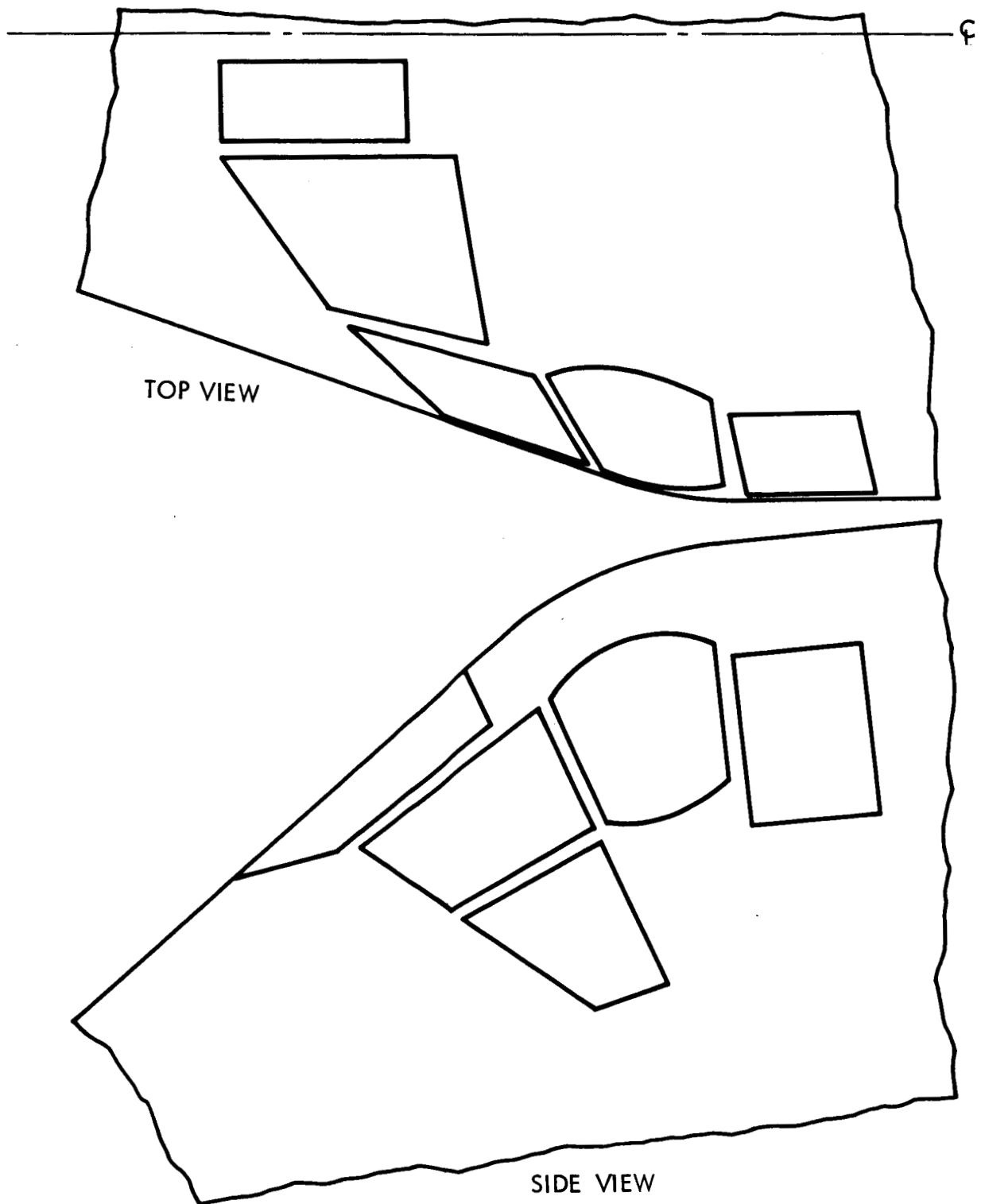
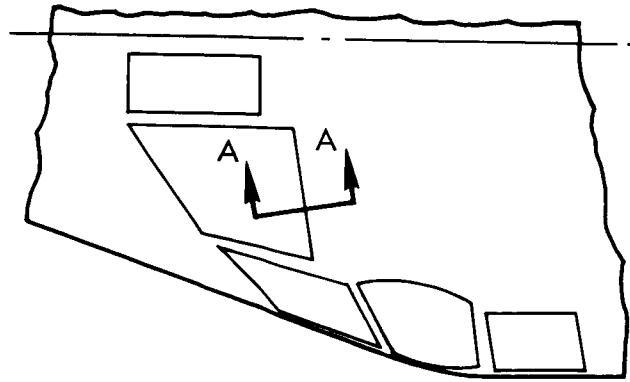


Figure A-1. Space Shuttle Orbiter Window Location and Approximate Configuration



TYPICAL WINDSHIELD PLAN VIEW

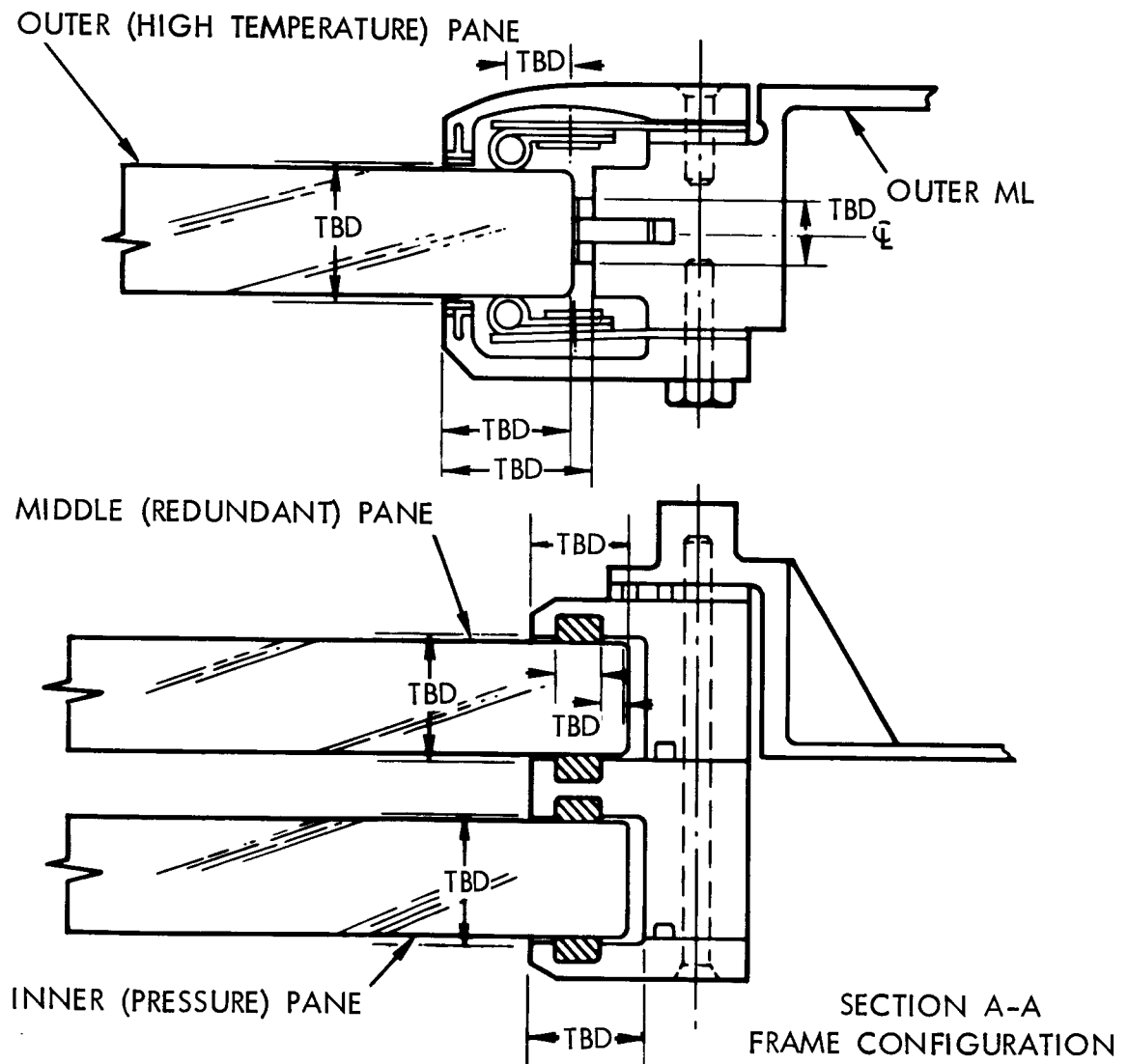


Figure A-2. Seal Configuration for Window Panel

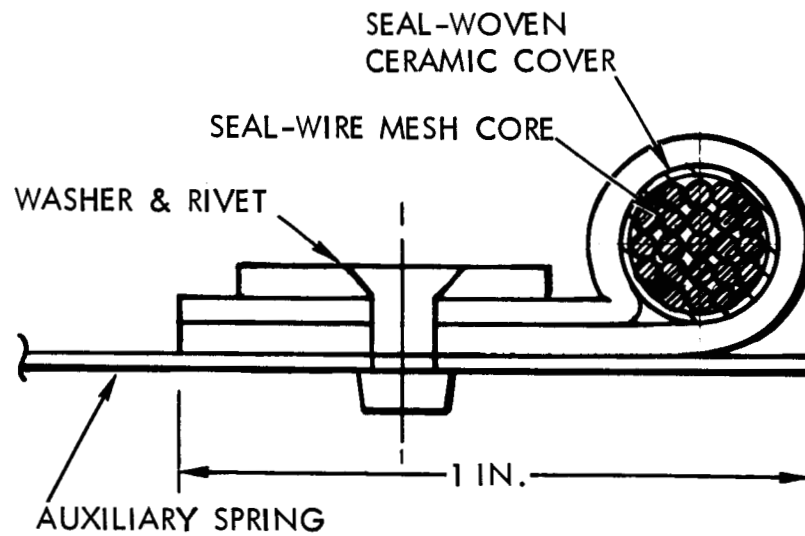


Figure A-3. Tadpole Type Design of Outer Window Seal

3.1.2.3 The outer window seal has a woven ceramic cloth cover and mesh cable core.

3.1.2.4 A Rene' 41 auxiliary spring in the form of a cantilever leaf is placed in series with the outer seal to provide auxiliary springback.

3.1.2.5 The outer window seal does not seal hermetically but hinders gas and particle flow so that the pilot's vision is not hindered.

3.1.2.6 The inner window seal shall consist of two 0.275-inch diameter and one 0.139-inch diameter "O" rings to provide hermetic sealing. The leakage rate shall be a maximum of 0.1 standard cubic inch per minute per linear foot of seal length at room temperature.

3.1.3 Major Components List. The windshield system shall consist of the following:

<u>Drawing</u>	<u>Component</u>
TBD	Main Frame
TBD	Support Frame
TBD	Retainer Frame
TBD	Retainer Bolts
TBD	Outer Seal
TBD	Centering Spring
TBD	Inner Seal
TBD	Middle Seal
TBD	Outer Glass Pane
TBD	Middle Glass Pane
TBD	Inner Glass Pane

3.2 Characteristics

3.2.1 Functional. The windshield glass system shall function as follows during the operational and mission life of the system prior to or following any single environment or combination of environments as defined in 3.2.5.

3.2.1.1 The windshield system shall provide the Space Shuttle Orbiter pilot and/or commander sufficient visibility to allow safe, efficient visual landings, cruises, orbital operations, payload operations, and takeoffs at any Orbiter-compatible airfield in daylight or darkness. This visual capability shall not require runway visual references, lighting or markings different from those utilized for commercial aircraft takeoffs and landings.

3.2.1.2 The minimum angles of unimpaired vision available to the pilot as provided by the windshield system and as measured from the pilot's design eye position shall be as follows:

3.2.1.2.1 Between 2 degrees beyond the worst transient yaw condition inboard and 20 degrees outboard provide visibility from the pre-flare entry altitude to visually observe; (1) the glide slope "aim-point," (2) the full length of a 10,000 foot runway with worst case transient in pitch attitude, and (3) sufficiently beyond the far end of the runway to be able to distinguish the surrounding terrain from the runway.

3.2.1.2.2 Between 2 degrees beyond the worst transient yaw condition inboard and 20 degrees outboard provide sufficient visibility to observe 2 degrees below the horizon at main gear touchdown with the maximum tail scrape angle.

3.2.1.2.3 At all points between 60 and 100 degrees left azimuth, vision shall be 18 degrees up and 20 degrees down. Sufficient head room shall be provided for the pilot to move his eye position 14 inches outboard so as to allow a minimum vision of 40 degrees up and 35 degrees down.

3.2.1.2.4 Between 20 and 60 degrees left azimuth, the vertical angle up shall increase from the smaller to the larger angle and the down angle shall be that which is resolved when a line is faired smoothly between the down angle at 20 and 60 degrees left azimuth.

3.2.1.2.5 The minimal requirements of paragraphs 3.2.1.2.1 through 3.2.1.2.4 for left hand seat of the pilot shall apply to the right hand seat of the commander relative to the right azimuth instead of the left azimuth. Specifically, the visibility requirements shall be symmetrical about the longitudinal axis of the orbiter so as to provide a comparable visual envelope for the pilot and commander.

3.2.1.3 Incidence angles for the visual axis and the contour of the windshield system of the crew compartment shall result in the least possible optical distortion within the limitations imposed by aerodynamic, structural, and fabrication considerations.

3.2.1.4 The optical properties of the windshield panes shall not deteriorate substantially as a result of being subjected to the environments defined in 3.2.5.

3.2.1.5 The elements of the windshield shall not exceed the temperature limits of Table A-1.

Table A-1. Temperature Limits

Window Elements	Maximum Design Temperature
Outer Pane	1270°F
Middle Pane	570°F
Inner Pane	300°F
Hermetic Seal of Inner and Middle Panes	400°F

3.2.1.6 The individual window panes shall be designed to be of sufficient thickness to withstand the pressure loads applied over the operation life as specified in paragraph 3.2.2.2. The design pressure loads are indicated in Table A-2. Specific design geometry determines thickness.

3.2.1.7 No special design precautions need be taken to assure windshield integrity from damage by rain erosion, hail, or bird impact during operations.

3.2.1.8 Windows shall be designed to provide the capability to clear windows of rain, fog, and frost.

3.2.2 General Structural. The window panes shall meet the following structural requirements over the life expectancy of the windshield system.

3.2.2.1 The minimum modulus of rupture shall be as specified in paragraph 3.2.3 or 3.2.4, as applicable, and shall be called out in the individual window pane drawings.

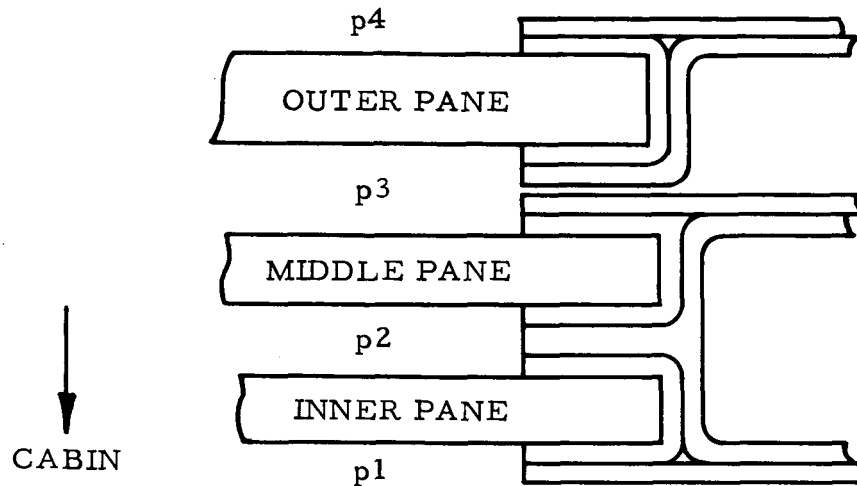
3.2.2.2 The operational service life shall be a minimum of 700 days consisting of 100 missions of seven days each.

3.2.3 Structural for Annealed Glass. The annealed glass window panes shall be capable of passing a proof test to the proof stress level determined by the procedure outlined in Figure A-4.

3.2.4 Structural for Thermally Tempered Glass. The thermally tempered glass window panes shall be capable of passing a proof test to the proof stress level determined by the procedure outlined in Figure A-5.

3.2.5 Structural for Chemically Tempered Glass. The chemically tempered glass window panes shall be capable of passing a proof test to the proof stress level determined by the procedure TBD.

Table A-2. Window Pressure Loads



Condition \ Pressure in psi	p1	p2	p3	p4	p1-p2	p2-p3	p3-p4
Descent	17.2 ^B	0 ^D	14.7	14.7	17.2	-14.7	0
Cabin Pressure Loss	0	17.2 ^E	0	0	-17.2	17.2	0
Boost-Dyn Crush	-	-	0	8	-	-	-8
Boost-Dyn Burst	-	-	8	0			8

A - Reg valve pressure = 14.7 ± .5 psia (for ref. only)

B - Positive relief valve pressure = $17 \begin{smallmatrix} +0.2 \\ -0.4 \end{smallmatrix}$ = 17.2 psia max

C - Negative relief valve pressure = -2.0 psig (for reference only)

D - Assume slow venting to space

E - Assume previous slow venting to cabin relief valve pressure

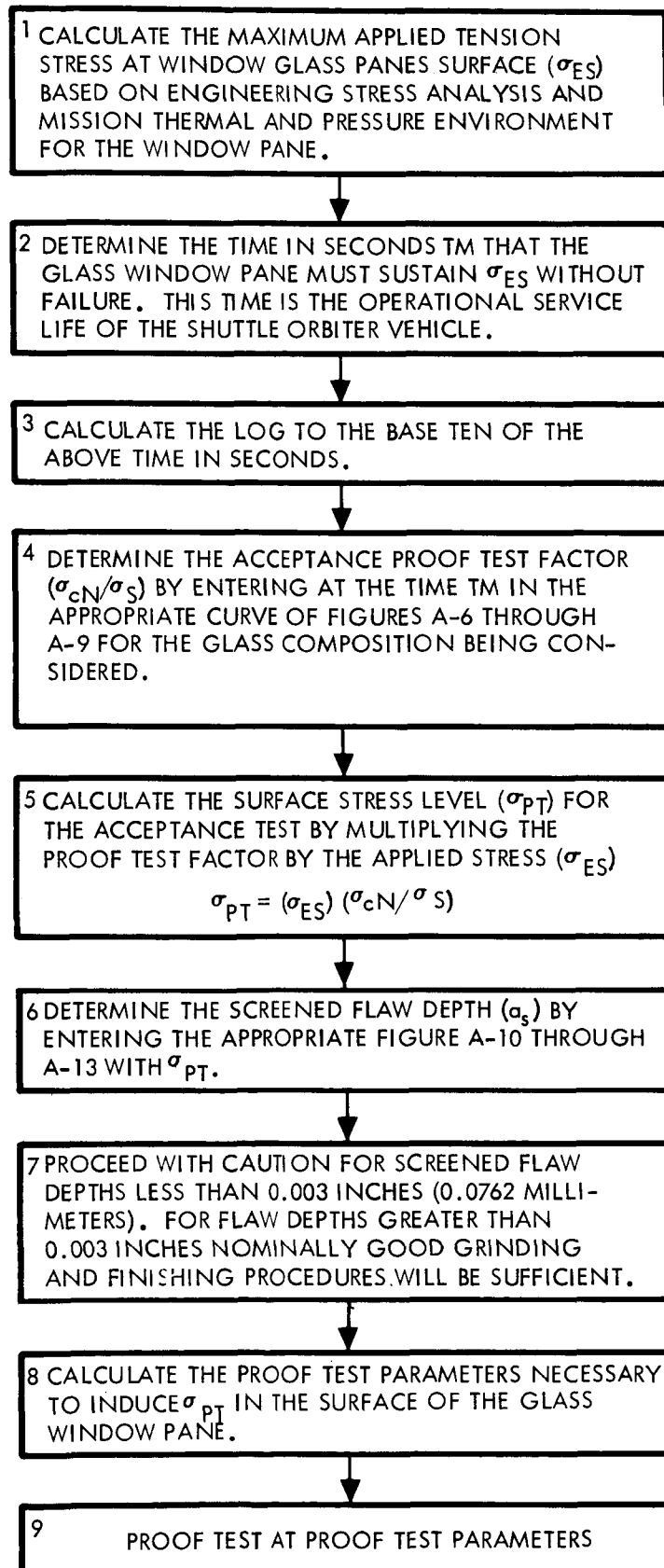


Figure A-4. Analysis Logic for Annealed Glass—Proof Test

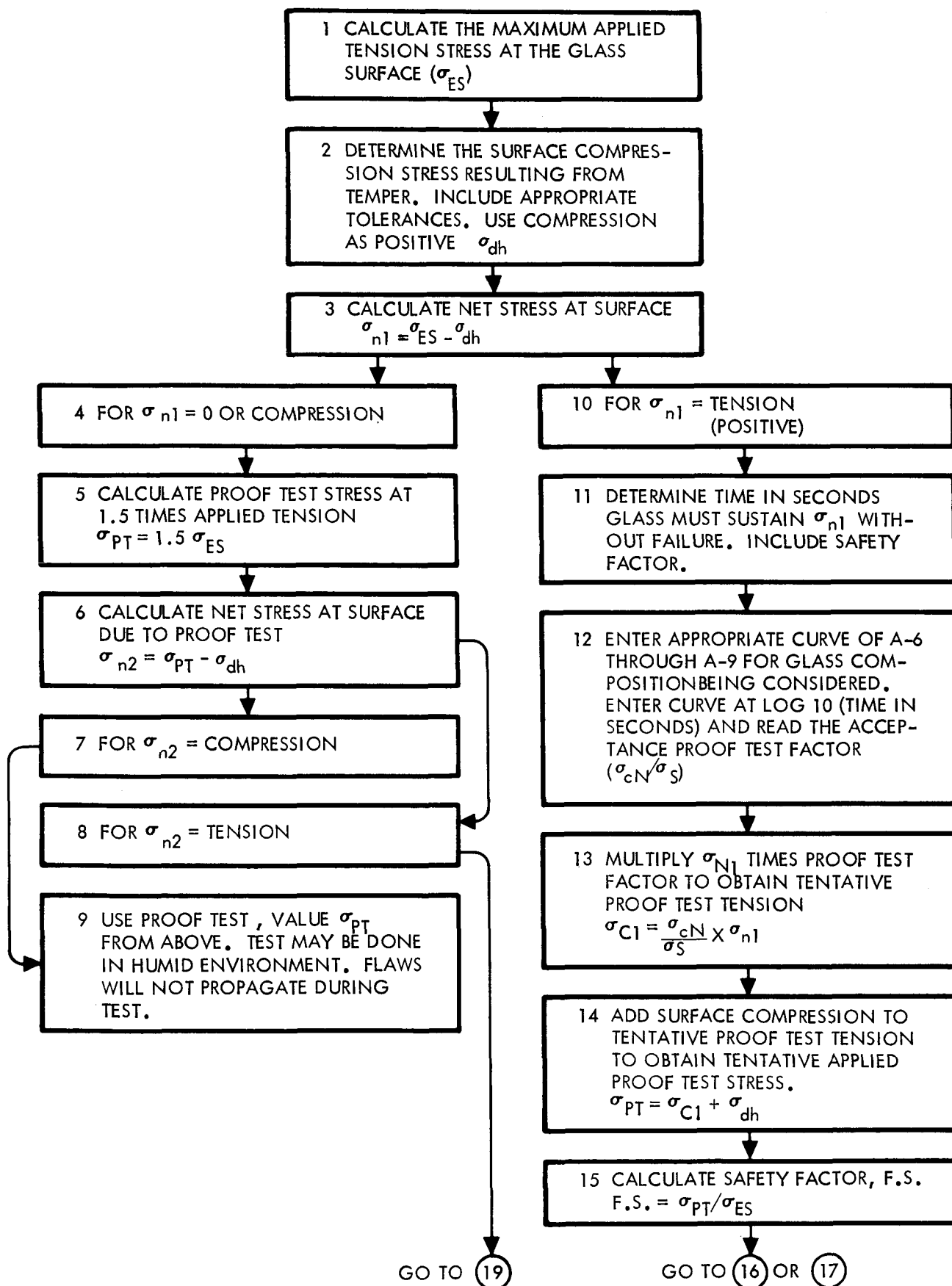
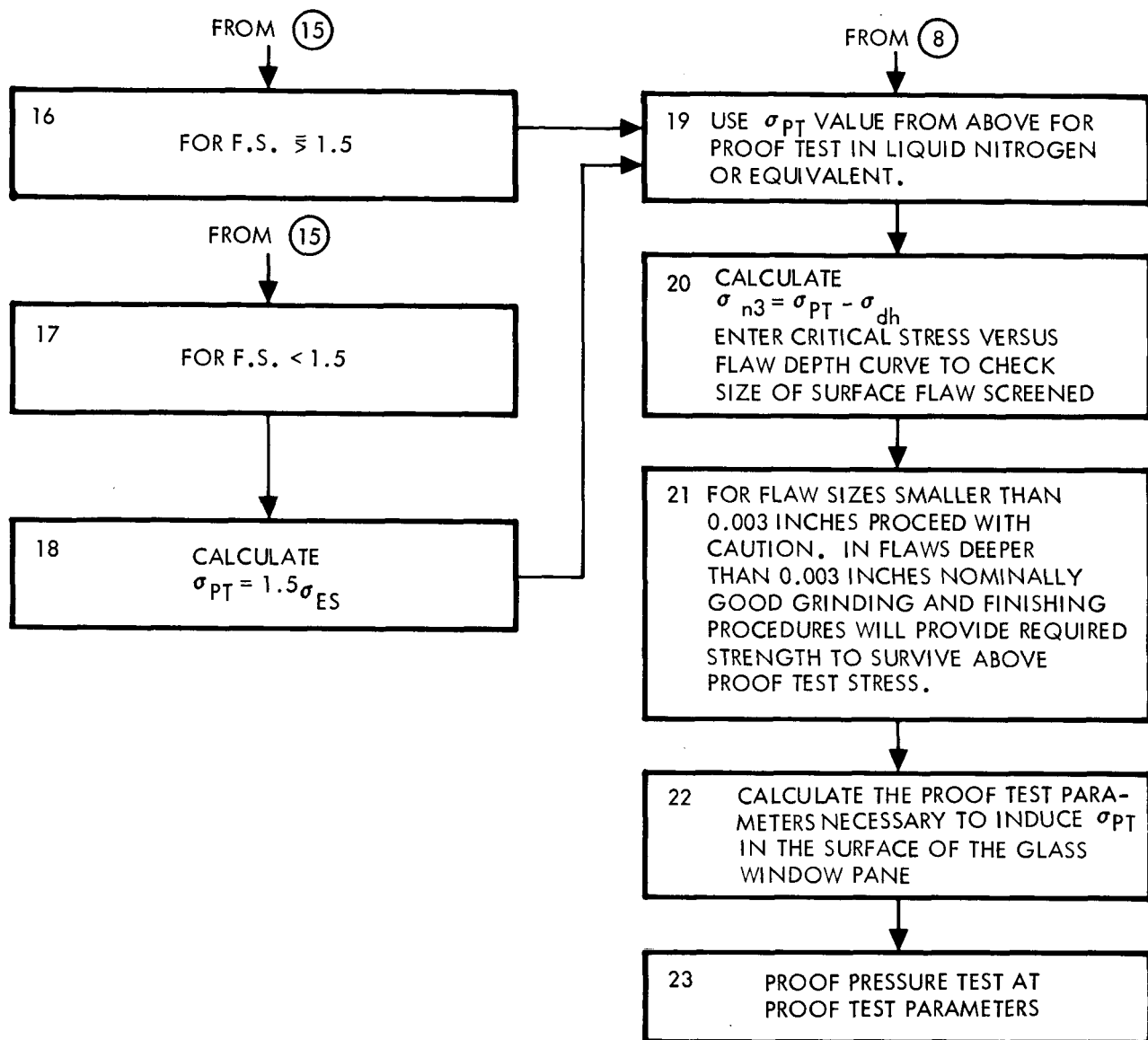


Figure A-5. Analysis Logic for Thermally Tempered Glass (Sheet 1 of 2)



σ_{dh} = SURFACE STRESS DUE TO THERMAL TEMPER (POSITIVE IN COMPRESSION)
 σ_s = APPLIED SURFACE STRESS
 σ_{n1} = NET SURFACE TENSION IN SERVICE
 σ_{PT} = APPLIED SURFACE STRESS IN PROOF TEST
 σ_{n2}, σ_{n3} = NET SURFACE STRESS IN APPLIED TEST
 F.S. = FACTOR-OF-SAFETY
 σ_c = CRITICAL STRESS (AT WHICH FAILURE OCCURS IMMEDIATELY FOR A CRITICAL FLAW SIZE)

Figure A-5. Analysis Logic for Thermally Tempered Glass (Sheet 2 of 2)

3.2.6 Reliability

3.2.6.1 The windshield glass system shall be of the fail safe design concept with respect to failure of either the inner (pressure) window or the outer (hot) window. The middle window of the three-pane configuration shall provide the required redundancy.

3.2.6.2 The inner window shall be of the fail safe design concept with respect to internal pressure leakage with a redundant seal element provided along any potential leak path.

3.2.6.3 The reliability of the outer window pane shall be 0.999 or greater relative to meteoroid environment as specified in section 3.2.8.2.

3.2.7 Maintainability

3.2.7.1 The outer window pane of each window shall be inspected for surface flaws prior to each flight. Any pane with a penetration exceeding that which could produce a meteoroid protection reliability factor of less than 0.999 shall be replaced prior to flight.

3.2.7.2 Repair/replacement methods shall be developed to meet the following requirements.

3.2.7.2.1 Repair/replacement of outer panes shall be accomplished in (TBD) hours maximum. Refurbishment activity involving removal and/or replacement of one or more window panes shall not require more than an average of (TBD) manhours per window pane involved.

3.2.7.2.2 Repair/replacement of window panes shall not require any special environmental conditioning of the total vehicle. Replacement of a pane shall be possible in a covered uncontrolled environment. Any environmental requirements (including cleanliness, dust catching, etc.) shall be provided as part of the repair technique.

3.2.7.2.3 Repair/replacement of individual windows shall be made without any damage to the rest of the windshield system or other structures of the orbiter vehicle.

3.2.7.3 The windshield system shall be designed such that the requirement for special tools and devices to install, in-place repair, or remove a window pane is minimal.

3.2.8 Environmental Conditions.

3.2.8.1 Transportation, Ground Handling, and Storage. The window pane shall be capable of meeting the requirements specified herein after exposure to the following conditions:

(a) Temperature (Air)

Air Transportation	Minimum ambient of -55 F for 6 hours Maximum ambient of +115 F Maximum compartment of +190 F for one hour and +150 F for 6 hours
Ground Transportation	Minimum ambient of -23 F Maximum ambient of +115 F Maximum compartment of +190 F for one hour and +150 F for 6 hours
Storage	
Ambient	25-105 F
Sheltered	25-105 F
Controlled	60-80 F
Assembly	Equivalent to controlled environment

- | | |
|---------------------|--|
| (b) Pressure | From sea level (1050 millibars) to 35,000 feet (239 millibars) |
| (c) Solar Radiation | 360 Btu/ft ² /hr for 6 hours per day over a two week period |
| (d) Humidity | Per paragraph 3.2.1 and 3.2.2 of NASA TMX 64589 |
| (e) Lightning | Table 9.1 of NASA TMX 64589 |
| (f) Rain | Table 4.1 of NASA TMX 64589 |
| (g) Hail | Paragraph 4.4.1 of NASA TMX 64589 |

- (h) Sand and Dust Paragraph 6.d of NASA TMX 64589
- (i) Fungus Section XI of NASA TMX 64589
- (j) Salt Spray Paragraph 10.2.1 of NASA TMX
64589 with an exposure time of
48 hours
- (k) Ozone Three years exposure including
72 hours at 0.50 ppm, 3 months at
0.25 ppm, and remainder at 0.05 ppm
- (l) Shock The window pane shall be installed
in its package and meet the transit
shock requirements specified in
Table A-3.

Table A-3. Transit Shock Requirements

Weight of Panel and Package	Largest Dimension (inches)	Height of Drop (in.)	Requirement	Total No. of Drops
Under 100 pounds (man-packed and man-portable)	Under 36	48	Drop on each face, edge, and corner per Procedure A Para. 4.1.3.3.1*	26
	36 and over	30		
100 to 200 pounds	Under 36	30	Drop on each corner per Pro- cedure A Para. 4.1.3.3.1*	8
	36 and over	24		
200 to 1,000 pounds	Under 36	24		
	36 to 60	36	Drop on each corner per Pro- cedure B Para. 4.1.3.3.2*	8
	Over 60	24		
Over 1,000 pounds	No limit	18	Drop on 4 edges and 2 corners per Procedure C Para. 4.1.3.3.3	6
*of NASA TM X-64589				

(m) Sinusoidal vibration as experienced in any direction:

<u>Gross Wt of Package</u>	<u>5 to 26.5 cps</u>	<u>26.5 to 52 cps</u>	<u>52 to 500 cps</u>
Less than 50 pounds	± 1.56 g	0.043 inch d.a.*	± 6.00 g
50 to 300 pounds	± 1.30 g	0.036 inch d.a.	± 5.00 g
300 to 1,000 pounds	± 1.30 g	0.036 inch d.a.	NA
Over 1,000 pounds	± 1.04 g	0.029 inch d.a.	NA

*d.a. - double amplitude

3.2.8.2 Flight. The window panes shall be capable of meeting the requirements specified herein after exposure to the following conditions, singly or in combination.

(a) Atmosphere (pressure, temperature, and density)	
Horizontal Flight	Paragraph 14.7 of NASA TMX 64589
Launch	Tables 14.2, 14.10, and 14.11 of NASA TMX 64589
Entry	Table 14.8 of NASA TMX 64589
(b) Rain	Table 4.1, 4.2, and 4.4 of NASA TMX 64589
(c) Hail	Paragraph 4.4.1 of NASA TMX 64589
(d) Lightning	Table 9.1 of NASA TMX 64589
(e) Solar Constant	428 Btu/ft ² /hr
(f) Radiation (100 to 500 NM)	Paragraph 2.4.1 of NASA TMX 64627
(g) Meteoroid Flux	Paragraph 3.1 of NASA SP8013
(h) Pressure (on-orbit)	10 ⁻¹⁰ Torr
(i) Aerodynamic Heating	TBD
(j) Plume & Fluid Impingement	TBD

- (k) Induced Temperatures TBD
- Liftoff TBD
- On-orbit TBD
- Entry initiation
 (400,000 feet) Those temperatures resulting from a combination of ascent heating and an orbital stay from 1400 to 4500 seconds during which the entire vehicle is exposed to a solar flux of 428 Btu/ft²/hr
- (l) Applied Loads TBD
- (m) Acoustic Noise TBD
- (n) Shock Exposure to 163 db sound level with a sound spectrum (TBD).

- (1) Landing - Rectangular pulses of the following peak accelerations, time durations and number of applications in the minus Z direction during landing:

<u>Acceleration</u>	<u>Duration</u>	<u>Applications</u>
0.23g peak	170ms*	22
0.28	280	37
0.35	330	32
0.43	360	20
0.56	350	9
0.72	320	4
1.50	260	1

*ms - milliseconds

3.2.9 Transportability. The windshield system and components shall be designed so as to be capable of being handled and transported to using facilities, without damage or degradation, utilizing available methods of transport with the item prepared for shipment in accordance with Section 5 requirements.

3.3 Design and Construction

3.3.1 Materials Parts and Processes

3.3.1.1 The design and layout of the windshield system shall be coordinated with the locations of internal light sources, light baffles, and the orientation of reflective surfaces for an optimum configuration to minimize reflections of objects, both within and outside the crew compartment to minimize interference with the pilots' vision.

3.3.1.2 A maximum effort shall be expended to meet the requirements of section 3.3.2 without the use of coatings. Should coating be necessary the windows with coated panes shall be optically homogenous and free of optical distortion.

3.3.1.3 Tooling marks (tong marks) due to handling during the tempering operation shall be located on the glass pane as indicated on the drawing. Tooling marks shall be as small as possible and not interfere with intended function of the glass pane.

3.3.1.4 The glass window pane serial and drawing number shall be marked on the edge of the glass as specified on the drawing.

3.3.2 Optical Requirements

3.3.2.1 Each window shall provide a minimum visible white light transmittance of 70 percent at an incidence angle normal to the window surface.

3.3.2.2 Each window shall provide an optical density equal to or greater than 3, or transmittance of 0.1 percent for ultraviolet radiation from 180 to 290 millimicrons wavelength ($m\mu$) at an incidence angle normal to the window. An optical density of 4 or transmittance of 0.01 percent in the range of 180 to 290 millimicrons wavelength shall be a design goal.

3.3.2.3 Each window shall provide an optical density equal to or greater than 1, or transmittance of 10 percent for infrared radiation between 800 and 2500 millimicrons wavelength ($m\mu$) at an incident angle normal to the window surface. Infrared transmission of less than a density of 2 or transmittance of 1 percent for infrared radiation between 800 and 2500 millimicrons wavelength shall be a design goal.

3.3.2.4 The windshield glass pane shall be fabricated in such a manner that optical distortion is held to a minimum. The glass shall be free of flaws which impede the windshield visibility.

3.3.3 Interchangeability and Replaceability

3.3.3.1 All parts having the same part number shall be completely interchangeable with respect to form, fit, and function.

3.3.3.2 Interchangeability of corresponding windows from Orbiter to Orbiter shall be a design goal. Interchangeability of corresponding window panes from corresponding Orbiter window to Orbiter window is a requirement.

3.3.4 Safety. The windshield system shall comply with the following safety requirements.

3.3.4.1 Component or element failures shall not propagate sequentially to other elements of the windshield system.

3.3.4.2 The elements of the windshield system shall withstand the maximum expected loads due to thermal expansion and structural distortion throughout the operational service life.

3.3.4.3 Materials which can shatter shall not be used in inhabited compartments unless positive protection is provided to prevent fragments from entering the cabin environment.

3.3.4.4 Materials selected for use shall not present ignition, flammability, toxic, noxious, contamination or shock sensitivity hazards within crew areas.

3.3.5 Human Engineering Requirements. The windshield glass system shall be designed and function in accordance with the requirements specified in MIL-H-46855 except as follows:

(Exceptions TBD)

3.3.6 Human Engineering Design Criteria. The windshield glass system shall be designed and function in accordance with the criteria specified in MIL-STD-1472A except as follows:

- (1) All equipment that may be handled, maintained, or operated by flight personnel shall be designed to the projected 1980 time frame 5 to 95 percentile anthropometric measurements for both male and female.
- (2) (Other exceptions TBD)

4. QUALITY ASSURANCE PROVISIONS

4.1 General Requirements

4.1.1 Responsibilities. The seller shall be responsible for implementing the quality assurance requirements of this specification. The windshield glass system may be included on the major test articles. The seller may elect to utilize these tests to supplement his in-house program, but should plan an independent program satisfying the requirements of 4.2.1.

4.1.2 Traceability. Traceability shall be provided by assigning a traceability identification to each window pane and providing a means of correlating each to its historical records, and conversely, the records must be traceable to each window pane. As part of the historical records for each window pane a planar map of the surface shall be provided that will indicate the location and depth of surface flaws as they are determined at the various inspection points. The planar map will remain with each window pane until installation in the vehicle at which time it will become part of the vehicle records.

4.1.3 Test Conditions

4.1.3.1 Standard Test Conditions. Environmental standard test conditions for tests required by this specification shall be atmospheric pressure of 30 plus or minus 2 inches of mercury at a temperature of 77 plus or minus 11 F and at a relative humidity of 80 percent or less.

4.1.3.2 Test tolerances shall be used as specified in MIL-STD-810, except as otherwise stated herein.

4.1.3.3 Transit Shock Test

4.1.3.3.1 Procedure A. The window pane shall be installed in its package and allowed to drop freely onto a floor or barrier of two-inch thick solid plywood, backed by either concrete or a rigid steel frame, from height shown in Table 3. The package shall strike the floor or barrier once on each face, edge, and/or corner in sequence, so that upon impact a line from the struck face, edge and/or corner to the center of gravity of the glass window pane and package is perpendicular to the impact surface.

4.1.3.3.2 Procedure B. The window pane shall be installed in its package. With the longest dimension parallel to the floor, the package shall be supported at the corner of one end by a block 5 inches in height, and at the other corner or edge of the same end by a block 12 inches in height. The opposite end of the package shall then be raised to the height shown in Table 3 at the lowest unsupported corner and allowed to drop freely onto a

floor of 2 inch thick solid plywood backed by either concrete or a rigid steel frame. The package shall strike the floor once at each of the corners in sequence.

4.1.3.3.3 Procedure C. The window pane shall be installed in its package. One edge of the base of the package shall be supported on a sill 5 to 6 inches in height. The opposite edge shall be raised to a height of 18 inches and allowed to drop freely onto a concrete floor or barrier. The package shall strike the floor or barrier once on each edge of the base of the package. One corner of the base of the package shall be supported on a block approximately 5 inches in height. A block nominally 12 inches in height shall be placed under the other corner of the same end. The opposite end of the package shall be raised to a height of 18 inches at the lowest unsupported corner and allowed to fall freely onto a concrete floor or barrier. The package shall strike the floor or barrier once on each of two diagonally opposite corners of the base of the package. When the proportions of width and height of the package are such as to cause instability in the cornerwise drop, edgewise drops shall be substituted. In such instances two more edgewise drops on each end shall be performed.

4.2 Quality Conformance

4.2.1 Verification Cross Reference Matrix. The seller shall verify the requirements of Sections 3 and 5 in accordance with the methods specified in Table A-4. The seller shall propose verification methods where they are not specified by the buyer.

4.2.2 Verification Methods

4.2.2.1 Development. During development of the window panel, the seller shall perform the research required to obtain evidence of suitability and to establish optimum material combinations, fabrication processes, tolerances, weights, and costs. The development testing shall be sufficiently comprehensive to provide reasonable assurance that the window panes will successfully complete the verification program.

4.2.2.2 Qualification. Qualification tests shall be performed to verify compliance of the unit with the Section 3.2.5 and 5 requirements. Compliance may be demonstrated by analysis with approval by the buyer.

4.2.2.3 Acceptance Tests. Prior to delivery and as a condition of acceptance the seller shall conduct at least the acceptance tests shown in Table A-5 on each window pane. The seller shall suggest other tests and test methods if applicable. Each end item shall be carefully examined with

Table A-4. Verification Cross Reference Matrix

Verification Method

- | | | |
|----------------------|------------------------|-------------------|
| 1. Analysis | 4. Test | |
| 2. Simulation | | |
| 3. Assessment | a) Development | |
| | b) Qualification | Seller-Conducted |
| a) Inspection | c) Acceptance | |
| b) Design Review | d) Vehicle Acceptance | } Buyer-Conducted |
| | e) Pre-Flight Checkout | |
| N/A - Not Applicable | f) Horizontal Flight | |
| | g) Vertical Flight | |
| | h) Major Ground Test | |

Sections 3 and 5 Requirement Numbers	N/A	Verification Method												Section 4.0 Requirement Number
		1	2	3a	3b	4a	4b	4c	4d	4e	4f	4g	4h	
3.1	X													4.2.2.2
3.2.1		X					X							
3.2.1.1		X	X											
3.2.1.2		X	X											
3.2.1.3	X													4.2.2.1, 2
3.2.1.4		X		X		X	X							
3.2.1.5		X												
3.2.1.6		X				X	X	X						
3.2.2							X	X						4.2.2.1, 2, 3
3.2.3		X						X						4.2.2.3
3.2.4		X						X						4.2.2.3
3.2.5		X						X						4.2.2.3
3.2.6		X												4.2.2.3
3.2.7			X											
3.2.8	X													
3.2.9		X		X										
3.3.1.2	X													4.2.2.3
3.3.1.3				X										
3.3.1.4				X										
3.3.2		X				X		X						
3.3.3	X													4.2.2.1, 2
3.3.4		X												
3.3.5	X													
3.3.6	X													
5.1	X													4.2.2.1, 2
5.2		X				X	X							

respect to material, workmanship, weight, drawing requirements, identification, and marking to assure conformance with the requirements of this specification. Testing shall be in accordance with Table A-5 and the remaining paragraphs in this section.

4.2.2.3.1 Each glass window pane shall be proof tested to establish that the required strength values are satisfied. The glass window pane shall be subjected to proof tests to the stress levels specified by paragraphs 3.2.3, 3.2.4, and 3.2.5.

4.2.2.3.2 The specimen, either annealed or tempered glass, shall be tested in liquid nitrogen and need not be predried. As an alternative for annealed glass only, the glass window pane may be dried at 300°C in a nitrogen gas stream of less than 0.017 percent relative humidity prior to test and tested at room temperature in a vacuum of 10^{-5} torr or in super dry nitrogen with a relative humidity of less than 0.017 percent. When so dried the glass is not to come into contact with ambient air or any source of moisture prior to or during acceptance testing. When all net surface stresses are in compression as determined by analysis the proof test may be performed under ambient conditions of humidity for tempered glass only.

Table A-5. Acceptance Test Characteristics and Techniques

Characteristic to be Evaluated	Test Technique
Dimensions Weight Location of surface flaws Location of surface flaws Surface flaw depth (handling) Screened flaw depth and modulus of rupture Optical distortion Objectional reflections Identification and marking Optical transmission	Mechanical measurements Weighing scale Edge lighting test Reflected light at high incidence angle Optical micrometer, surface scratch gage Pressure proof test or coupon bending tests Visual Crew cabin mockup Visual inspection Photometer

4.2.2.3.3 The test factor used in the analysis for the proof levels shall be determined from the acceptance test ratio graphs as shown in Figures A-6 through A-9. The test factor shall be used on the operational service life specified in paragraph 3.2.2.2.

4.2.2.3.4 The visual surface flaws shall be marked as to location and depth on a map tracing of the planar surface of the glass pane and shall accompany the historical records for the particular glass pane throughout the remaining manufacturing cycle and be filed for reference during the operational life of the glass window pane.

4.2.3 Test Criteria.

4.2.3.1 Test Equipment Certification. Equipment used to measure item parameters shall be in accordance with MIL-STD-810 except as otherwise noted herein.

4.2.3.3 Adjustments and Repairs During Tests. No adjustments, repairs, or maintenance of window panes shall be allowed during tests unless approved by the Buyer.

4.2.3.4 Witnessing of Tests. The Buyer reserves the right to witness any test, in whole or in part, or to designate witnesses (in addition to those selected by the Seller) who have a "need-to-know" (e.g., consultants or government agencies).

5. PREPARATION FOR DELIVERY

5.1 General Requirements. The requirements specified herein govern the preparation of the window panes for shipment to all Buyer and Government Facilities or test sites.

5.2 Detailed Preparation. Packaging, handling and transportation shall be in accordance with applicable requirements of NHB 6000.1 (1A) as amended by the following subparagraphs.

5.2.1 Preservation and Packaging. Preservation and packaging shall be in accordance with the requirements of Level A of MIL-STD-794.

5.2.2 Packing. Packing shall be in accordance with the requirements of Level B of MIL-STD-794.

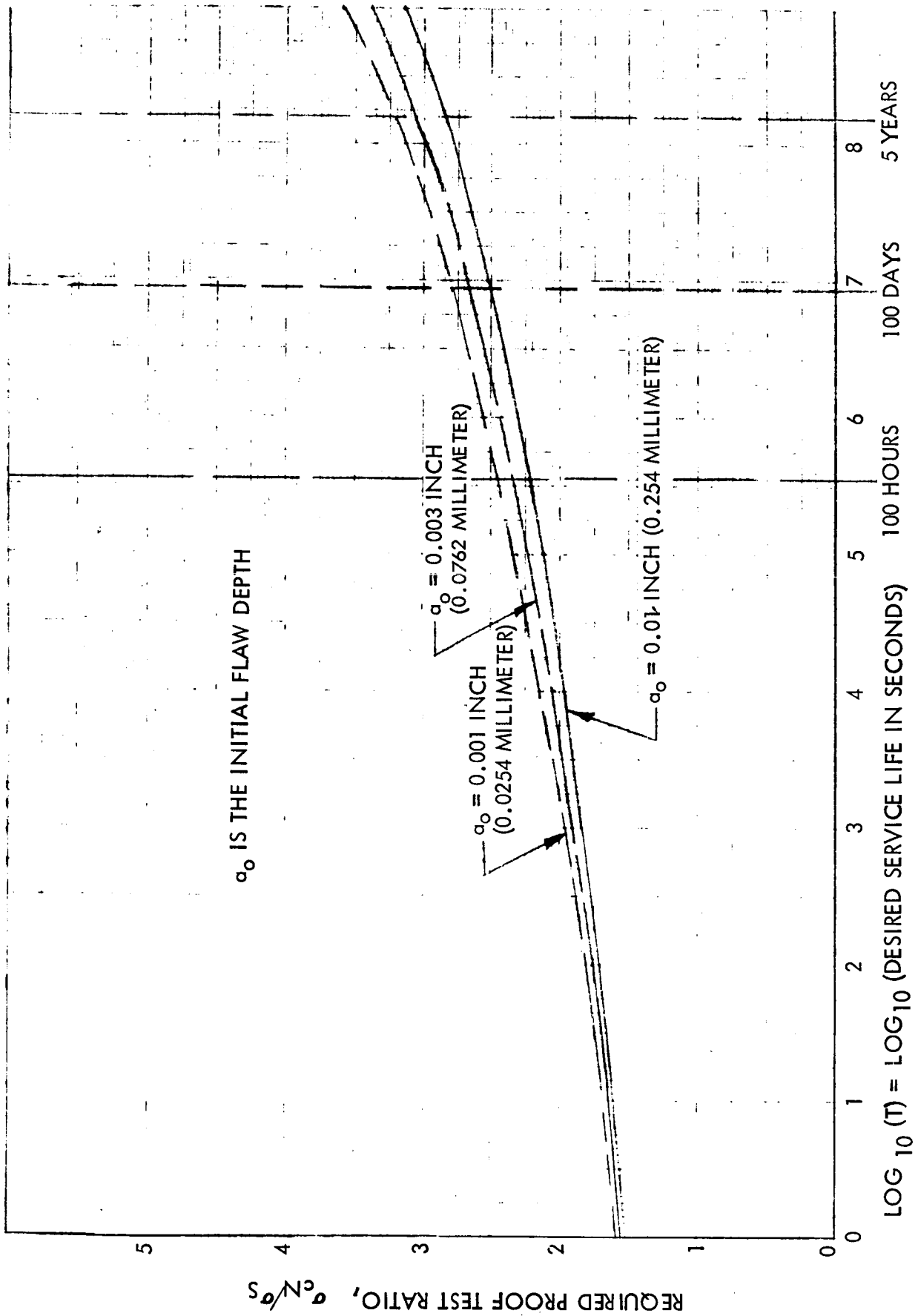


Figure A-6. Fused Silica Acceptance Test Ratio Graph

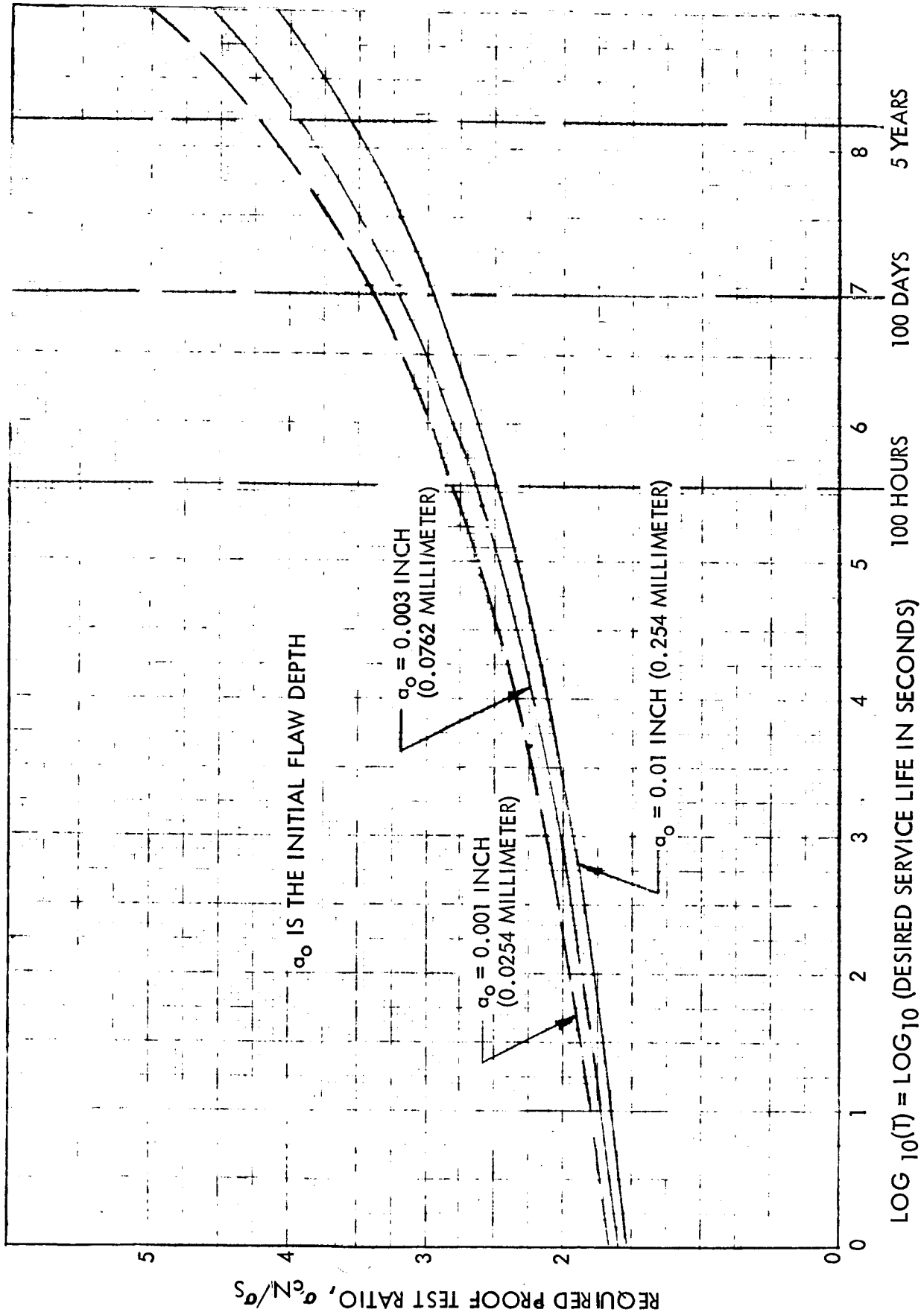


Figure A-7. Aluminosilicate Acceptance Test Ratio Graph

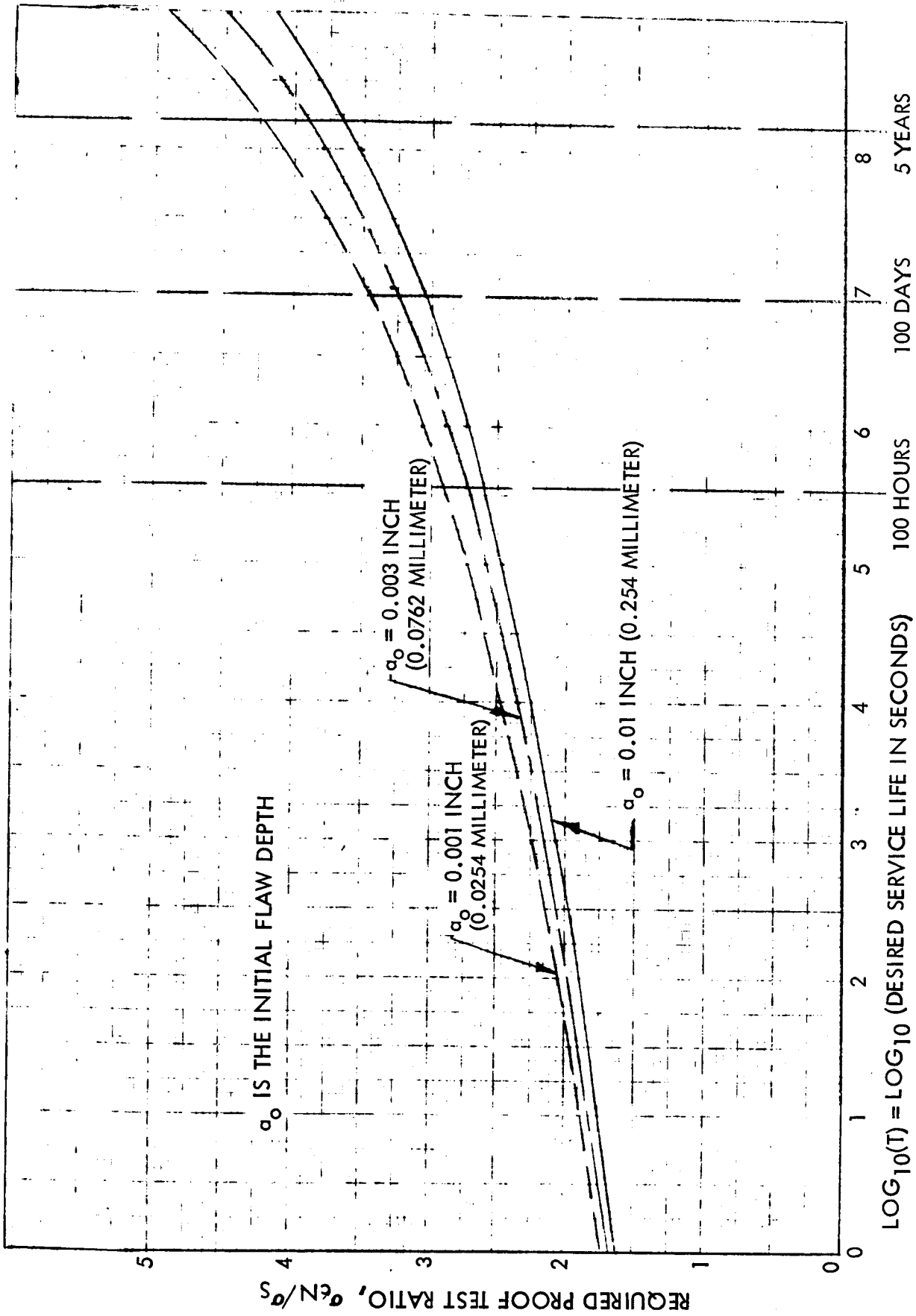


Figure A-8. Borosilicate Acceptance Test Ratio Graph

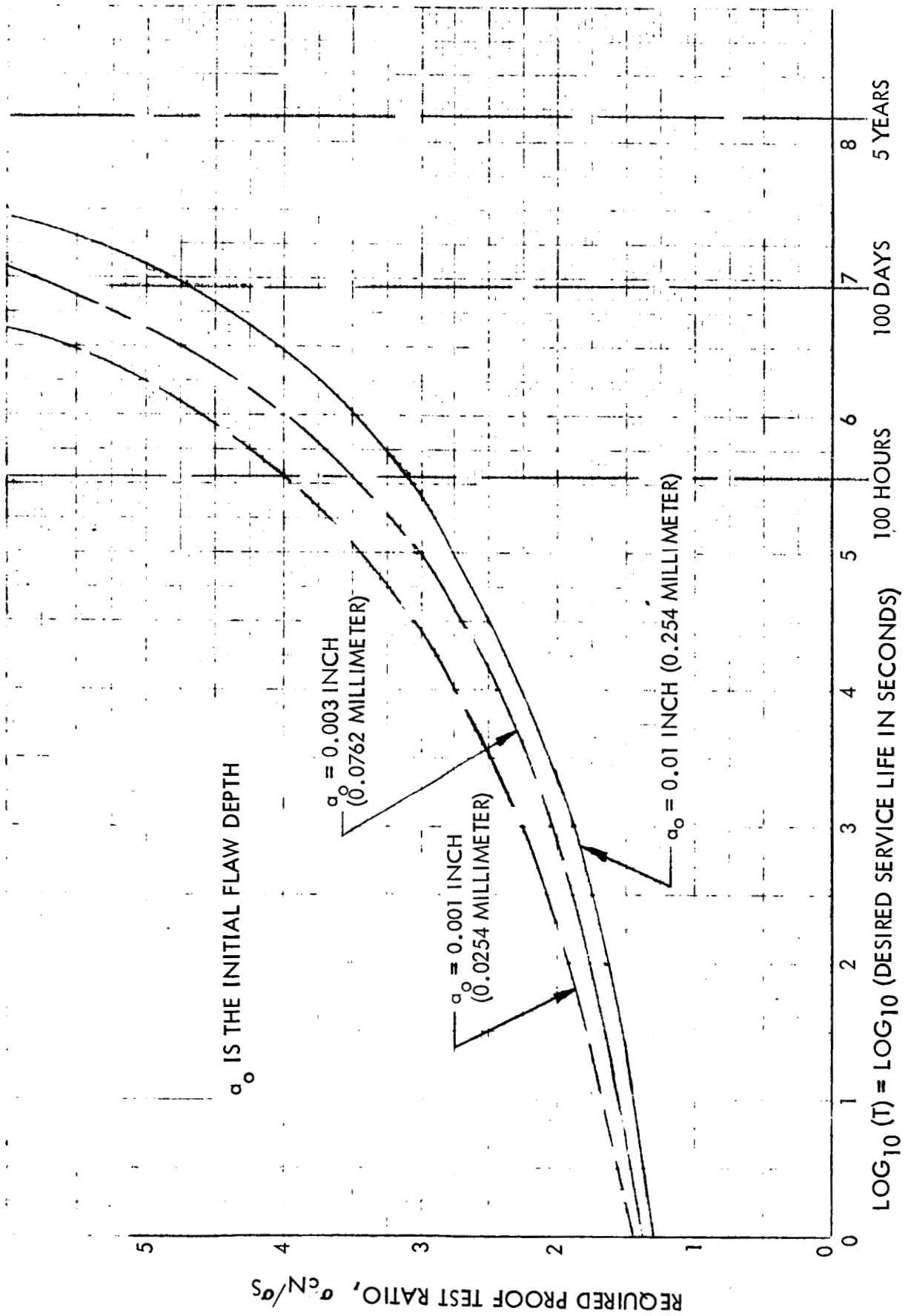


Figure A-9. Soda Lime Acceptance Test Ratio Graph

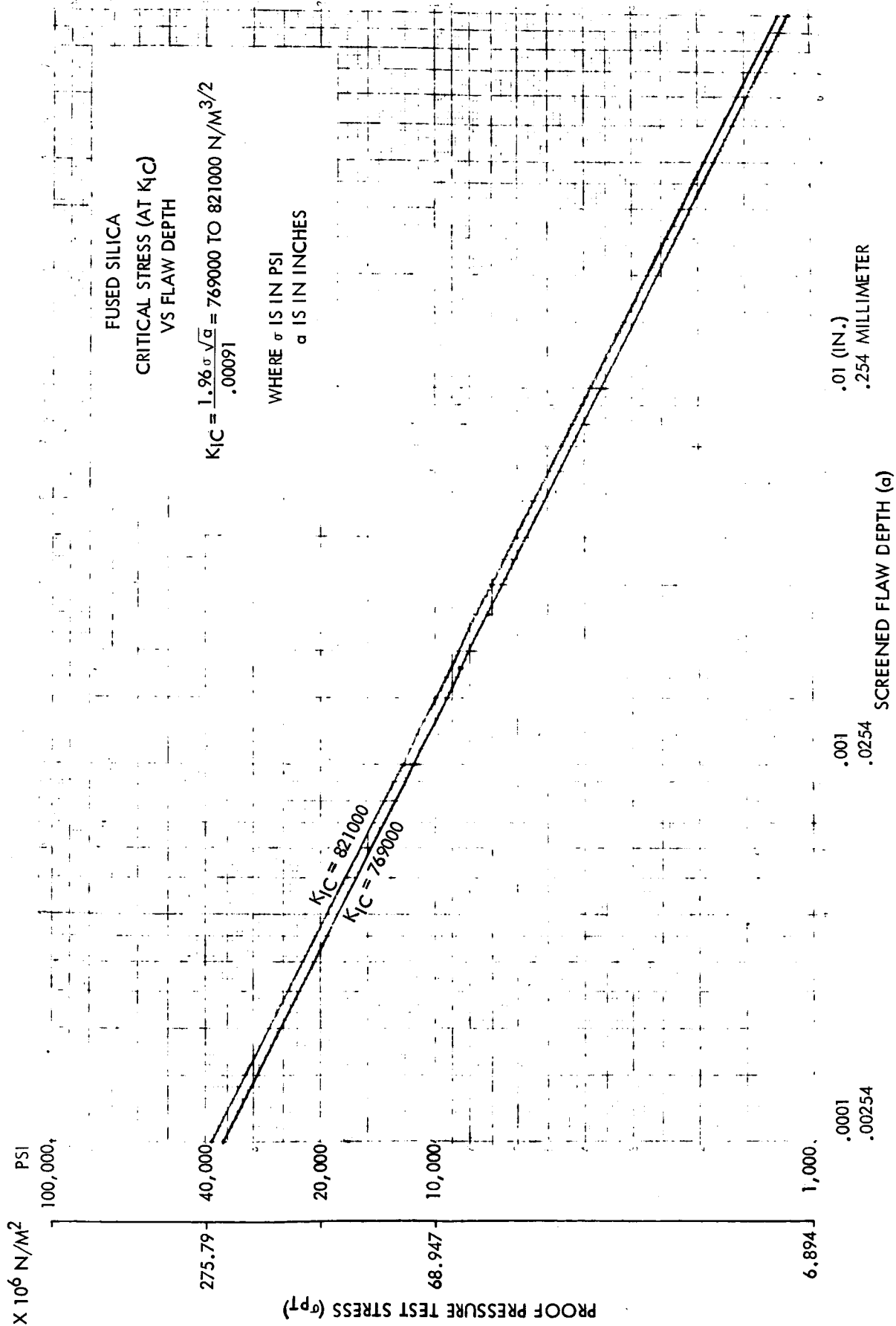


Figure A-10. Fused Silica Critical Stress Intensity Graph

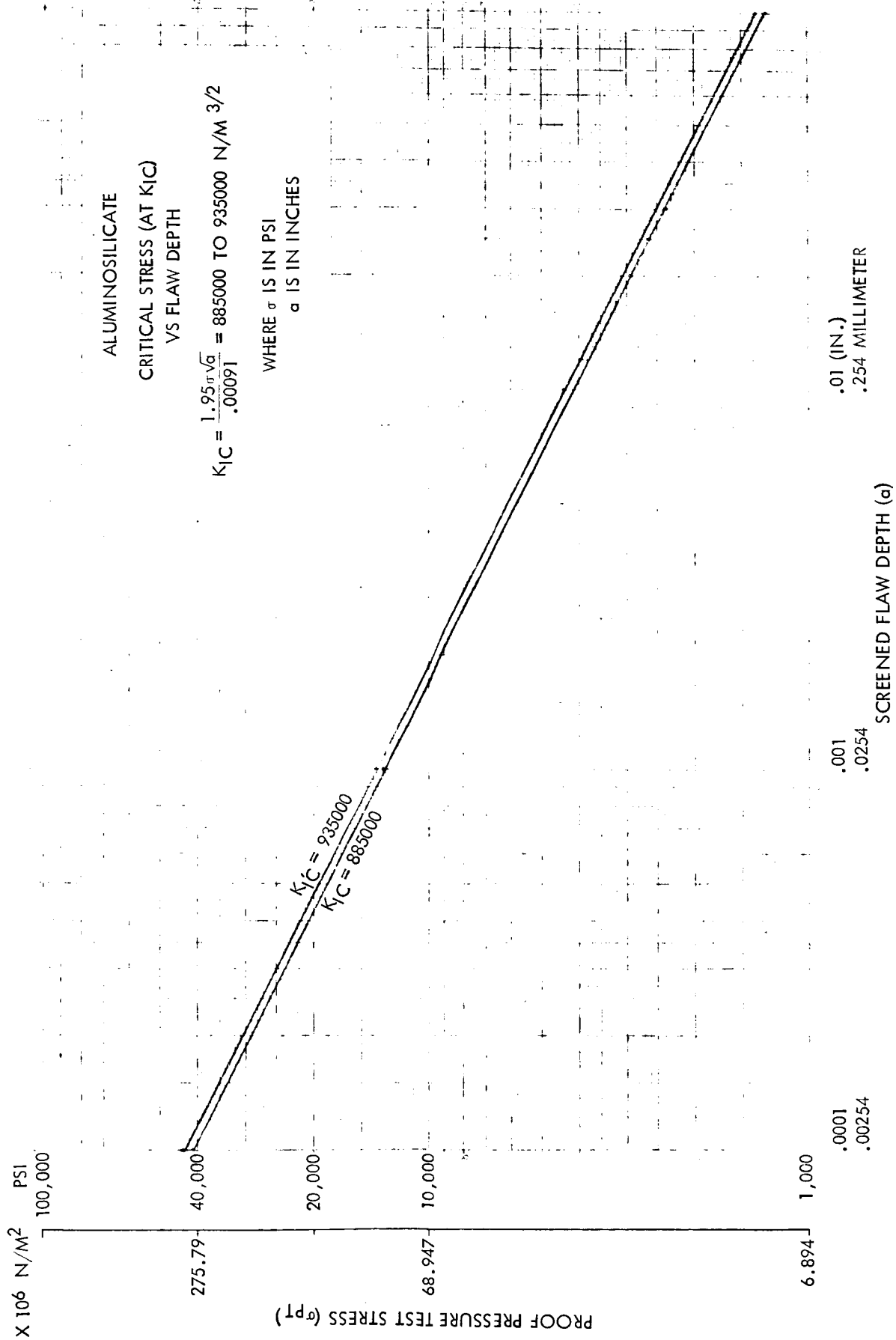


Figure A-11. Aluminosilicate Critical Stress Intensity Graph

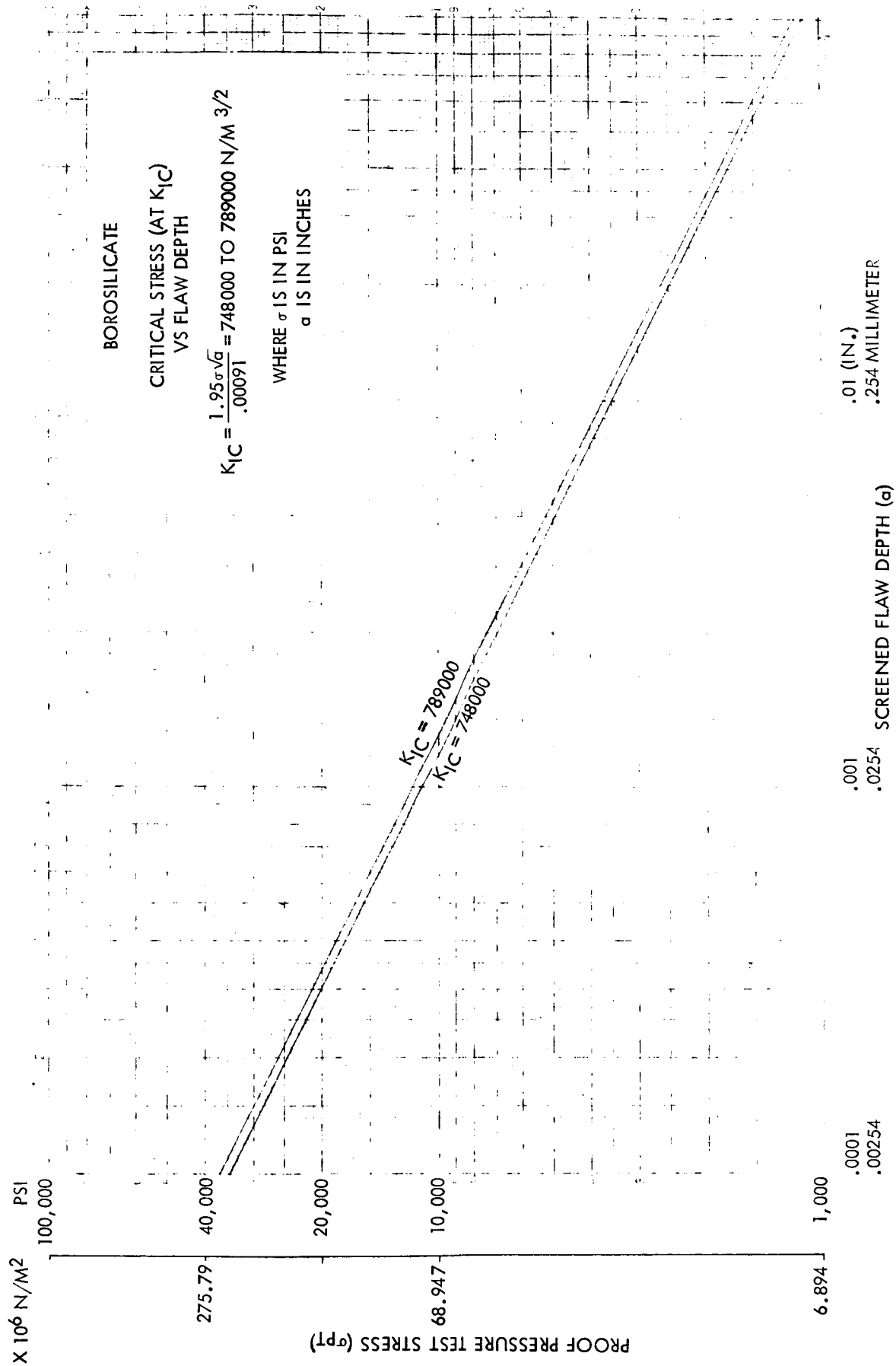


Figure A-12. Borosilicate Critical Stress Intensity Graph

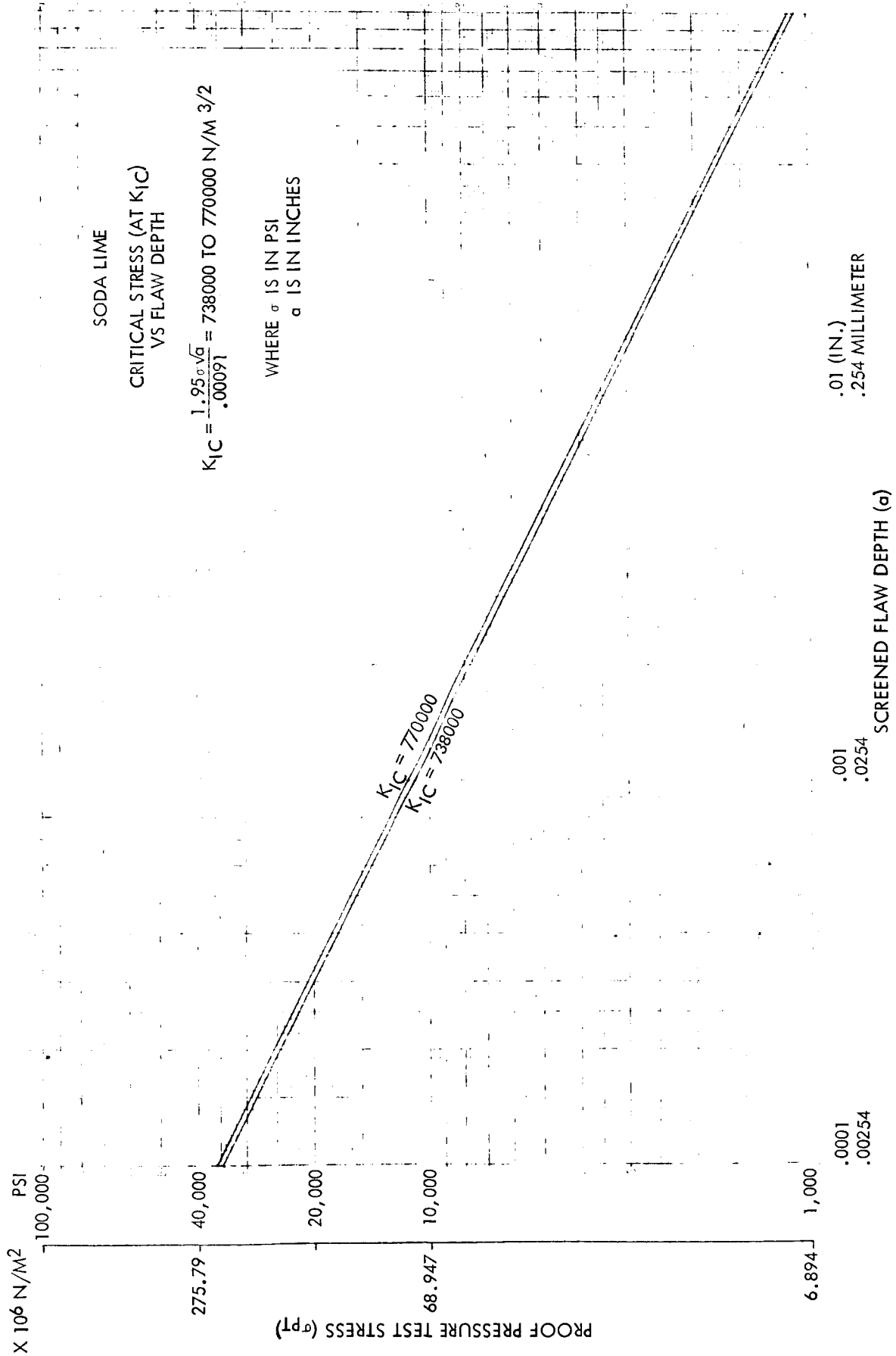


Figure A-13. Soda Lime Critical Stress Intensity Graph

5.2.3 Rough Handling Design Requirements. Preservation, packaging, and packing shall be designed so as to be capable of withstanding the Level A drop, impact, vibration, and superimposed load tests of MIL-STD-794, without degradation of the contained item and without damage to the packaging and container which would affect their utility.

5.2.4 Method II (Desiccation) Packaging. Items requiring Method II packaging shall comply with Level A requirements of MIL-STD-794.

5.2.5 Monitoring Devices. MIL-I-26860 humidity indicators shall be installed in the container wall or flexible barrier wall of all Method II packages. Other instrumentation for monitoring/recording in-transit environments (e.g., shock, vibration, temperature, etc.) shall be utilized as required herein.

5.2.6 Preproduction Package Tests. Package testing to verify the capability of the package to meet the Rough Handling Design Requirements shall be accomplished as required by the verification cross reference index in paragraph 4.2.1.

5.2.7 Packaging Data. Drawings, specifications, or other data defining method of packaging, handling, or transportation shall be supplied only as required by Data Submittal requirements of the Purchase Order.

5.2.8 Container Design Philosophy. Containers shall be modularized to facilitate the Seller's loading and securing of the window panes. Provisions shall be incorporated in each modular container for specific window panes which are to be applied to exact designated locations on the orbiter structure. (Buyer to identify sectionization breakdowns and schedule requirements for those locations). Modular container designs also shall include the requirements for ease of window pane access, container handling, storing, transporting, and identification. The complete packaging and shipping procedures and flow plans shall be approved by the Buyer.

5.2.9 Marking for Shipment. Interior and exterior containers shall be marked and labeled in accordance with MIL-STD-129 including precautionary markings necessary to ensure safety of personnel and facilities, and to ensure safe handling, transport, and storage. For hazardous materials, markings shall also comply with the requirements of applicable freight tariffs, requirements of the Department of Transportation, Atomic Energy Commission, and Code of Federal Regulators. Identification information and special markings on interior and exterior containers shall include:

NR/Space Division - Part Number (Obtained from "List of Components")

Item Name (Obtained from "List of Components")



Manufacturer's Type or Part Number (Supplied by Seller) _____

Quantity in Package _____ Traceability Identification _____

Age Control Marking _____

Serial Number (Manufacturer's part serial number) _____

Manufacturer _____

Purchase Order Number (Buyer purchase order number) _____

Date of Packaging and Level of Packaging and Packing _____

Manufacturer's Package Part Number (only for specially designed packages; not required for standard, off-the-shelf containers) _____

Reusable Container (for packages with reuse capability; not required for standard, off-the-shelf containers) _____

Reusable Container Do Not Destroy -

Retain for Reuse or Return to Material Stores

NASA Critical Item Label (Form 1368 series) - apply in accordance with NHB 6000.1(A)

6. DEFINITIONS

Acceptance Tests. Those tests performed on all units before shipment from the Seller's plant to determine that each unit meets the design and performance requirements of this specification.

Qualification Tests. Those tests performed on specifically fabricated items to demonstrate that the Seller End Item will meet the performance requirement of this specification.

Buyer. Contract issuing agency

Seller. Successful bidder receiving the contract to fabricate the glass windshield panes.

Failure. Any change in the window pane resulting in inability of the pane to meet the requirements of this specification for subsequent mission phases of the mission being flown or for any subsequent mission up to and including the 100th.

Seller End Item. For deliverable window pane items Seller End Items shall consist of all of the panes required for the final assembly, as indicated in delivery requirements of the Purchase Order.

Pilots Design Eye Position - The pilots design eye position is indicated in Figure (TBD). All pilot eye positions are measured relative to this position.

Glide Slope "Aim-Point" - The glide slope aim-point is indicated in Figure A-14. This point is the straight line intercept of the glide path with the ground.

Optical Density - The optical density is the logarithm to the base ten of the quantity the intensity of the incident light divided by the intensity of the light transmission through the glass pane.

$$D = \log_{10} \frac{I_0}{I}$$

Light Transmittance Percent - The light transmittance is the percentage of intensity of transmitted light through the pane relative to the incident intensity of light.

$$P \% = \frac{I}{I_0} \left(\frac{I}{100} \right)$$

Screened Flaw Depth - The maximum depth of flaw that is possible without causing failure in the proof test.

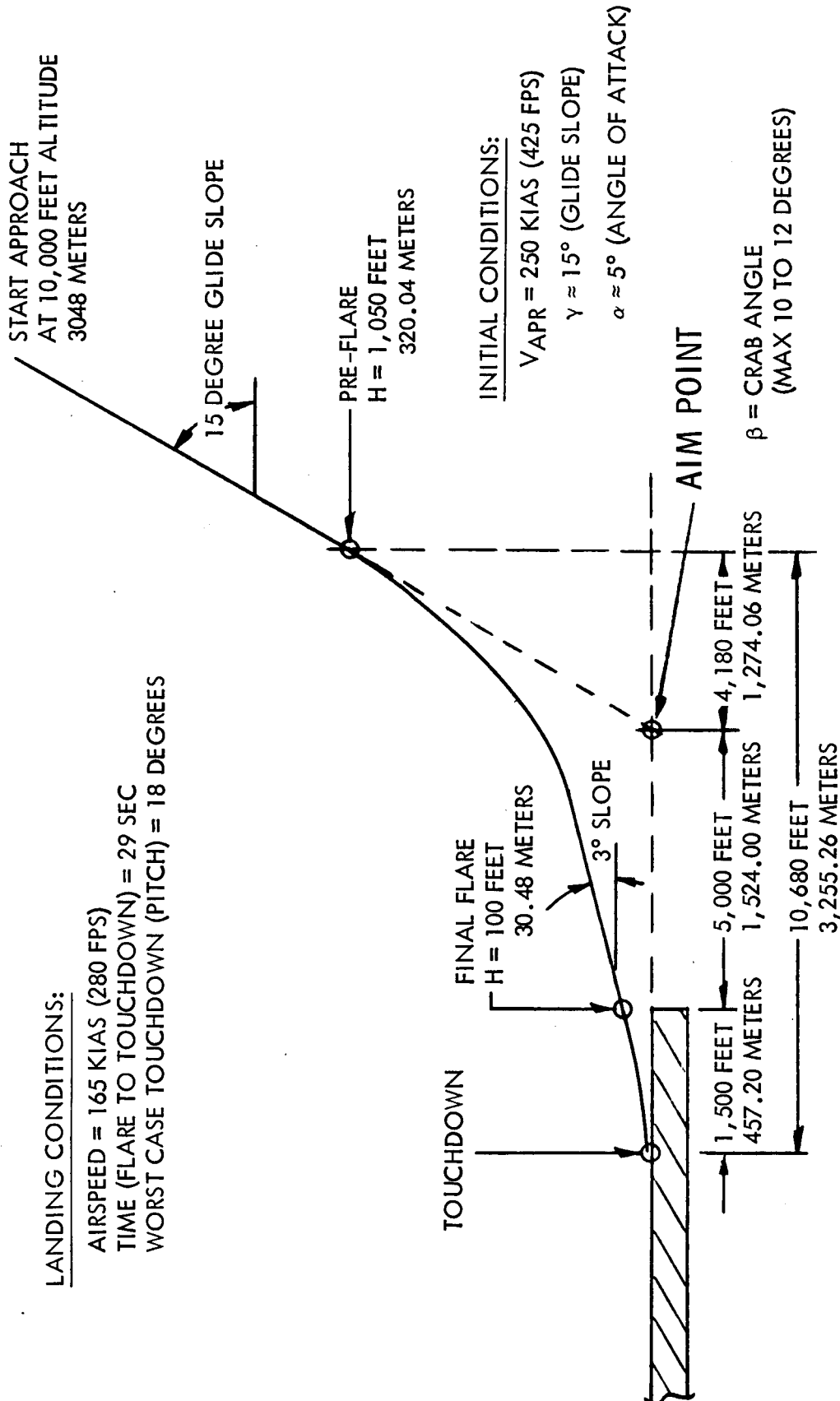


Figure A-14. Glide Slope Aim Point

APPENDIX B

EXAMPLES: PROOF-TEST CALCULATIONS, HEAT-TEMPERED GLASS

APPENDIX B

EXAMPLES: PROOF-TEST CALCULATIONS, HEAT-TEMPERED GLASS

This appendix gives examples of the procedure for determining proof test value for heat-tempered glass as diagrammed in Figure A-5 of Appendix A. For annealed glass the logic of Figure A-4 applies. However, the explanation for use of A-5 is applicable to the more simple annealed glass case. For symbols, see Nomenclature in main body of report.

Three cases shall be shown: Case I is the actual Apollo flight limit stress of 10,200 psi, Case II is a fictitious bending stress assumed at 14,700 psi. This case will cause the surface of the pane to be in tension with a F.S. ≤ 1.5 , Case III same as Case II except F.S. is > 1.5 .

Case I

When the limit bending stress is 10,200 psi wherein the surface of the aluminosilicate pane does not experience a tensile stress, the pane shall be analyzed in the following manner.

- 1.* $\sigma_{ES} = 10,200$ (limit tensile stress on surface due to external loading)
- 2.* $\sigma_{dh} = 13,700$ psi (on surface due to temper of glass)
- 3.* $\sigma_{n1} = \sigma_{ES} - \sigma_{dh}$
 $= 10,200 - 13,700$
 $= -3700$ psi
 (net surface stress, when the net surface stress is zero or compression multiply the external load by 1.5)
- 5.* $\sigma_{PT} = 1.5 \times \sigma_{ES}$
 $= 1.5 \times 10,200$ psi
 $= 15,300$ psi (Proof test stress)
- 6.* $\sigma_{n2} = \sigma_{PT} - \sigma_{dh}$
 $= 15,300 - 13,700$
 $= 1600$ psi (net surface tensile stress)
- 20.* Flaw depth screened 0.07 inch (on surface) (from Figure A-11 of Appendix A flaw is larger than 0.003 inch so nominally good grinding procedures are OK)

Case II

The following procedure shall be used when the net surface stress is in tension. Assume a case where the bending stress is 14,700 psi for aluminosilicate pane.

*Numbers refer to the Step Numbers in Figure A-5, Analysis Logic For Thermally Tempered Glass.

$$1.* \sigma_{ES} = 14,700 \text{ psi (limit bending stress on surface due to external loading)}$$

$$2.* \sigma_{dh} = 13,700 \text{ psi (on surface due to temper of glass)}$$

$$\begin{aligned} 3.* \sigma_{n1} &= \sigma_{ES} - \sigma_{dh} \\ &= 14,700 - 13,700 \\ &= 1000 \text{ psi (net tensile stress on surface)} \end{aligned}$$

$$11.* 100 \text{ hours service life} = 360,000 \text{ seconds}$$

$$12.* \sigma_{cN}/\sigma_S = 2.88 \text{ (from Figure A-7 of Appendix A at 100 hours)}$$

$$\begin{aligned} 13.* \sigma_{C1} &= 2.88 (1000) \\ &= 2880 \text{ psi} \end{aligned}$$

$$\begin{aligned} 14.* \sigma_{PT} &= \sigma_{C1} + \sigma_{dh} \\ &= 2880 + 13,700 \\ &= 16,580 \text{ (proof test stress in liquid nitrogen)} \end{aligned}$$

$$\begin{aligned} 15.* F.S. &= \sigma_{PT}/\sigma_{ES} \\ &= 16,580/14,700 \\ &= 1.13 \text{ (safety factor (F.S.) must be } \geq 1.5) \end{aligned}$$

$$\begin{aligned} 18.* \sigma_{PT} &= 1.5 \sigma_{ES} \text{ (increase the applied external bending stress by 1.5 factor)} \\ &= 1.5 (14,700) \\ &= 22,100 \text{ psi} \end{aligned}$$

$$\begin{aligned} 20.* \sigma_{n3} &= \sigma_{PT} - \sigma_{dh} \\ &= 22,100 - 13,700 \\ &= 8400 \text{ psi (net surface tensile stress)} \end{aligned}$$

*Numbers refer to the Step Numbers in Figure A-5, Analysis Logic For Thermally Tempered Glass.

- 20.* Surface flaw greater than
0.0024 inch screened

(from Figure A-11 of Appendix A
flaw is less than 0.003 inch so
special precautions must be used
in grinding.)

Case III

The following example illustrates the procedure where the safety factor is greater than 1.5. Assume aluminosilicate with a bending stress equal to 6400 psi and the modulus of rupture = 16,000 psi, surface compressive stress is equal to 4000 psi.

- 1.* $\sigma_{ES} = 6400 \text{ psi}$
 - 2.* $\sigma_{dh} = +4000 \text{ psi}$
 - 3.* $\sigma_{nl} = \sigma_{ES} - \sigma_{dh} = 6400 - 4000 = 2400 \text{ psi}$
 - 11.* 100 hours service life
 - 12.* $\sigma_{cN}/\sigma_S = 2.88$ (from Figure A-7 of Appendix A)
 - 13.* $\sigma_{Cl} = \sigma_{cN}/\sigma_S \times \sigma_{nl}$
 $= 2.88 (2400)$ (net surface tensile stress at proof stress)
 $= 6930 \text{ psi}$
 - 14.* $\sigma_{PT} = \sigma_{Cl} + \sigma_{dh}$
 $= 6930 + 4000$
 $10,930 \text{ psi (proof stress)}$
 - 15.* F.S. = σ_{PT}/σ_{ES}
 $= 10,930/6400 = 1.70$ (factor of safety greater than 1.5 so
proof test value OK)
 - 20.* Flaws greater than 0.0015 inch
screened
- (from Figure A-11 of
Appendix A. Extensive care
must be taken in setting up and
executing grind and polish since
flaw is smaller than 0.003 inch).

*Numbers refer to the Step Numbers in Figure A-5, Analysis Logic For
Thermally Tempered Glass.